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Long-term Evaluation of Building Envelope Materials

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Long-term Evaluation of Building Envelope Materials

By

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Abstract

Long-term Evaluation of Building Envelope Materials

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The building envelope is arguably the most important aspect of a building besides its structure. It is the first line of defense against the environment and maintains comfortable humidity and air conditions. However, in contrast to structural components, the material specification and testing standards of the building envelope are less well defined, which leads to premature failure and costly maintenance. This thesis summarizes the research performed, the developed test, and the findings from ongoing research at the Durability Lab to evaluate the long-term performance of various building envelope materials.

Code requirements for tapes and self-adhered flashings are tabulated and compared with test results. It is determined that the adhesion requirements of these products are not well developed. In addition, the performance of tape products is also evaluated using shear adhesion testing. The study emphasizes the compatibility of the adhesives at a variety of temperature ranges.

Furthermore, materials testing of exterior plaster mixtures specified in ASTM C926 and common manufacturer's pre-blended mixtures is conducted. The study aims to

determine the physical and mechanical properties of exterior plasters. The variability of the coefficient of thermal expansion is found to correspond to different moisture conditions. Several ACI (American Concrete Institute) models are also introduced to predict the tensile strength and modulus of elasticity of plaster mixtures using their compressive strength. An additional model is developed to better characterize the plaster modulus. Strong agreement between the test results and models is observed.

Finally, the report summarizes the results from large-scale tests performed on 32 clear penetrating water repellents, for which data were collected over three years. Prolonged exposure to UV radiation is found to have a significant impact on evaluation of the long-term durability of water repellents. The general behavior of “good” and “bad” products is also noted.

This research is part of an ongoing project at the University of Texas at Austin’s Durability Lab. The Durability Lab was formed by Building Diagnostics, Inc. to study the durability of building components. It is located at the University of Texas at Austin on the J.J. Pickle Research Campus. Other ongoing testing, including water-resistive barrier mockups, stucco panels, and elastomeric sealants, is not included in this thesis.

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Chapter 1: Introduction

1.1 BACKGROUND

Walls, roofs, windows, and doors all play a role in maintaining comfort within a building, but this is really made possible by the building envelope. The building envelope is the exterior or shell of a building that provides structural integrity, moisture control, temperature control, and air pressure boundaries. Each part of the building envelope comprises multiple components that work together to achieve the same goal of stopping or slowing the flow of air, water, or heat while providing the inevitable intrusion of water a means for the building to dry out.

Failure of the building envelope system can lead to aesthetic loss, corrosion, poor indoor air quality, mold, increased energy bills, and even structural deficiency. Generally, three factors lead to the premature failure of an envelope system: design deficiencies, material failure, and poor workmanship. Common mistakes related to inadequate design involve the specification of materials that are incompatible with one another when they come into contact or that do not meet the performance criteria for thermal movement, structural capacity, or water resistance. Issues also arise when materials fail to meet their published performance. Lastly, proper and informed installation is the key to ensure the intended performance of a product. These three factors are the cornerstone of each study conducted at the Durability Lab. Long-term testing of tapes and self-adhered flashing, exterior plaster, and clear penetrating water repellent suggest that only when these three factors are carried out properly does the building envelope behave efficiently and premature failures become far less common.

1.2 Scope of the Project

The research completed for this thesis was carried out to determine the field performances of different components of the building envelope. Most of the performed tests consist of extended outdoor exposure, as the best way to test the effects of a combination of factors including heat, humidity, wind, rain, and UV radiation is to place specimens under conditions that would be encountered in the field. While many waterproofing materials are exposed for 10–20 years prior to evaluation, the artificial weathering required for these products may only represent a couple of months of real outdoor exposure (NAHB Research Center, Inc. 2002). This project describes test results accumulated from years of data for tapes and water repellents testing. The data for exterior plaster and analysis described herein are generated by the author. Ultimately, the tests revolve around the same theme of building envelope durability.

1.3 Content

This thesis consists of three chapters, which each discuss the research performed, testing, and material characteristics. They also state how the information presented can be applied to improve the durability of building envelope components.

Chapter 2 encompasses the performance and durability of tapes and self-adhered flashing products. In particular, research is performed on the code requirements for tensile adhesion and its testing standard. This chapter also discusses the results of shear adhesion testing vs. temperature for over 500 tape specimens.

Chapter 3 covers testing completed on various ASTM-grade and manufacturers' pre-blended exterior plaster mixtures. To this end, ASTM test methods are applied to determine the compressive strength, split tensile strength, and modulus of elasticity for the hydraulic concrete used for the plaster mixtures. The coefficient of thermal expansion of these mixtures is also determined in different moisture conditions. Furthermore, the study introduces several ACI models to predict the mechanical properties of plaster.

Chapter 4 considers testing completed on clear penetrating sealers. Test results are tabulated from data collected over three years and clarify misconceptions in the industry. The general behavior of “good” and “bad” products in relation to their chemical composition is determined.

Chapter 5 provides an overall conclusion on the research and makes several recommendations to improve material specifications and testing.

1.4 SIGNIFICANCE

Many of the tests presented in this thesis are the results of literature reviewing, preliminary testing, and reconciliation with manufacturers and industry leaders. As such, each chapter presents technical information produced by those in that industry and how test procedures are constructed. The test results shed light on misconceptions in the industry and point out the inadequacy of standards and codes. Many of the test results and findings have been presented throughout the US in an attempt to improve material specifications and installation standards. Each chapter also discuss the behavior of materials under field conditions and recommendations for better practices, which ultimately improve the overall durability of a project.

Chapter 2: Suitability and Adhesion Requirements for Tapes and Self-Adhered Flashings

2.1 Problems Description

Although moisture problems in buildings can arise from several sources, the window–wall interface has been proven as one of the most critical factors for water intrusion. This problem has multiple causes, but improper flashing installation has been noted consistently and often poses a high risk of consequent damage to the building (Katsaros 2005). The use of self-adhered flashing products and construction tapes (referred to as "tapes" in this study) is becoming more widespread, as they provide a tight seal and ease of installation over mechanically fastened products and building sealants. In addition, tapes and self-adhered flashings are not only popular for sealing the window–wall interface but also for spanning gaps and waterproofing transitions in the building envelope. Since tapes and flashings are concealed behind cladding, it is crucial that they are durable and last for the lifetime of a building as repairs are not trivial and often require costly demolition and reinstallation. Most construction professionals are familiar with traditional rubberized asphalt self-adhered flashings ("peel and stick"), but acrylic and butyl tapes are becoming increasingly popular. To evaluate their performance, numerous construction tapes and flashings were tested on a variety of substrates and temperatures. This study explains the trends observed during testing, including the adhesive chemistry, compatibility, and durability of tapes on common substrates.

2.2 Testing Sample Description

Tapes and flashings are often an integral part of an air and water barrier. As defined by the IBC (International Building Code), flashings act to "prevent moisture from entering the wall or to redirect that moisture to the exterior" and "shall be installed at the perimeters of exterior door and window assemblies, penetrations and terminations of exterior wall assemblies…" During their service life, the IECC (International Energy Conservation Code) indicates that tapes will be stressed and must be "securely installed around the penetrations as to not dislodge loosen or otherwise impair the penetrations' ability to resist positive and negative pressure from wind, stack effect and mechanical ventilation." Tapes typically consist of three components: a carrier sheet (sometimes called a facer or top sheet), an adhesive membrane, and a release paper (protective liner). The carrier sheet often consists of polyethylene, polypropylene, or aluminum, while the most common adhesives are acrylic, butyl, and modified asphalt. The adhesives used in tapes consist of long-chain polymers, which interact with substrates similarly to liquid under pressure to create strong physical bonds.

In this study 25 tapes and self-adhered flashing products from various manufacturers were evaluated. In term of adhesives, 11 acrylic, 8 butyl, and 6 modified asphalt products were examined. Shear adhesion tests have been carried out since 2016 at the Durability Lab, in which tape products were evaluated on nine different substrates including plywood, OSB (oriented strand board) smooth side, OSB rough side, gypsum sheathing, ZIP sheathing, EPS (expanded polystyrene insulation sheet), Tape over Tape (to simulate lap joint), Tyvek Homewrap, and building paper. In addition, representative products were also selected and installed on an exposed sheathing with an integrated water barrier membrane in order to evaluate the products' long-term performance.

2.3 CODES AND STANDARDS

Tapes and self-adhered flashing products have not been broadly integrated into codes and standards. The industry currently relies on two major specifications established by the American Architectural Manufacturers Association (AAMA) and the Air Barrier Association of America (ABAA) Inc. Both associations specify the minimum requirements for various parameters of flashing products, such as top sheet tensile strength, cold temperature pliability, adhesion after water immersion, resistance to peel, water penetration around nails, and various adhesion strengths.

Many institutions refer to AAMA 711-13, *Voluntary Specification for Self Adhering-Flashing Used for Installation of Exterior Wall Fenestration Products*, for the minimum requirements for self-adhered flashings, such as:

- International Building Code, *Chapter 14 – Exterior Walls*
- International Residential Code, *Chapter 7 – Wall Covering*
- ASTM E2122-19, *Standard Practice for Installation of Exterior Windows, Doors, and Skylights*
- International Code Council's AC148, *Acceptance Criteria for Flexible Flashing Materials*

For adhesion requirements, AAMA 711-13 requires the product to have a minimum peel adhesion of 1.5 lbs/in under four conditions: laboratory, accelerated UV aging, elevated temperature, and thermal cycling. The test procedure for each condition is described in sections 5.3 to 5.6 in AAMA 711-13. The peel adhesion test is conducted using ASTM D3330, *Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape*, in which a 1" width x 12" length specimen is peeled at 90^0 at a rate of 5 mm/sec.

Under these conditions a peeling adhesion of 1.5 lbs/in can be easily achieved and may not promote the product durability.

However, the ABAA has stricter adhesion specifications in its *Process for Approval of Air Barrier Materials, Accessories, and Assemblies.* For a self-adhered air barrier and its accessories, the ABAA requires products to pass 5 lbf/in of peel or stripping strength (ASTM D903-98), 5 lbf/in of lab adhesion (ASTM D1876), and 16 psi of pull or tensile adhesion (ASTM D4541). The desired adhesive strength of 16 psi is possibly based on the cohesive strength of Dupont "Great Stuff" expanding urethane foam air seal, which dominates this market. This product is typically used to seal large gaps between window–wall interfaces prior to the installation of flashing. As a result, 16 psi tensile adhesion is established as minimum benchmark for the whole system.

2.4 Testing Methodology

2.4.1 Shear Adhesion Test

The shear adhesion test conducted in this study is loosely based on ASTM D3654, *Standard Test for Shear Adhesion of Pressure Sensitive Tapes*. The procedure was modified by affiliates of the Durability Lab based on experience and initial trial and error in an attempt to include weathering effects from UV radiation, wind, and rain (Garcia 2017). The specimens were prepared in accordance with ASTM D3654 and were cured for 72 hours in laboratory conditions as suggested by the manufacturers. Subsequently, the specimens were exposed outdoors on a rack facing south in order to receive maximum solar radiation. In addition to outdoor exposure, the authors also increased the area of the contact patch to 2" x 2" so that fewer specimen modifications were required, as 2” is a common tape width. This increase in contact patch size also prevents most tapes from immediately failing, which prolongs the weathering effects acting on specimens. Detailed procedures and analysis regarding the compatibility between adhesive and substrate are summarized in the article, “Defining and testing construction tape and flashing durability” (Garcia 2017). Figure 2.1 shows the testing apparatus that is set up outdoors at the J.J. Pickle Research Campus.

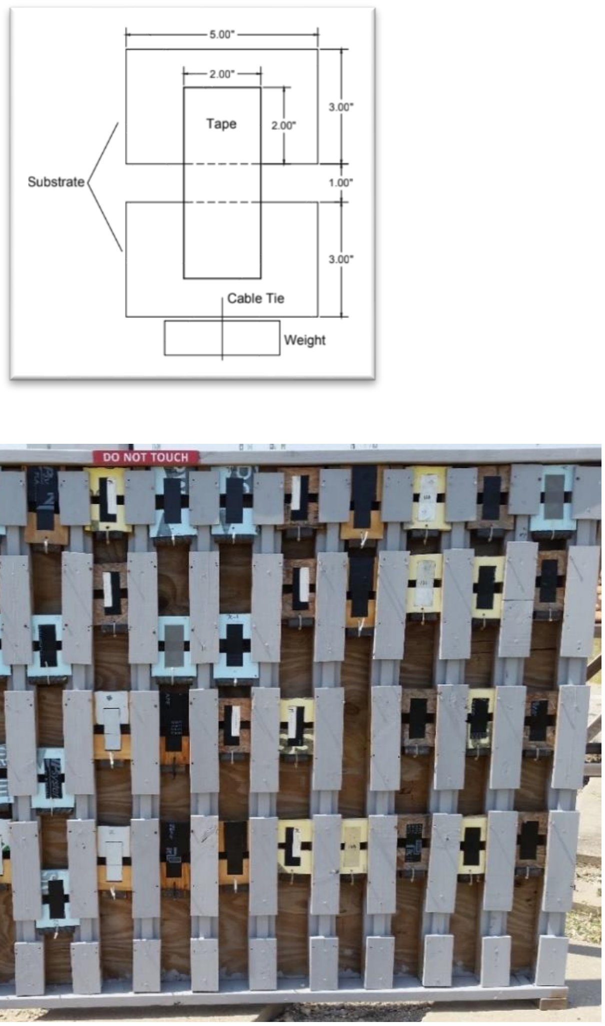
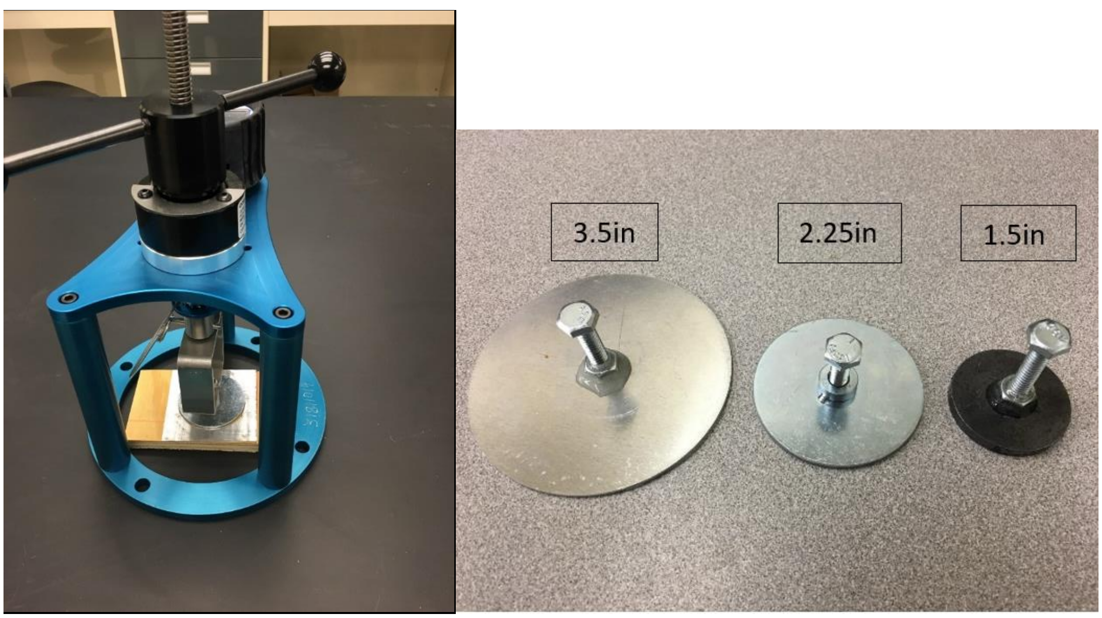


Figure 2.1: Testing apparatus used for the shear adhesion test

2.4.2 Tensile Adhesion Test

Following the AAMA’s *Process for Approval of Air Barrier materials, Accessories, and Assemblies*, the ASTM D4541 was selected to evaluate the products’ tensile adhesion. The tester used in this study is manufactured by COMTEN and is able to withstand a maximum load of 400 lbs (Figure 2.2a). The tensile adhesion can be calculated by dividing the maximum load by the specimen contact area. A parametric study on the testing apparatus was also included in this research due to disagreement between the test result and the published performance of the products. The results indicate that the tensile adhesion is independent of the specimen size (Figure 2.2b), but significantly proportional to the loading rate. This variation of tensile adhesion vs. loading rate is discussed in section 2.5.2.



(a) (b)

Figure 2.2: (a) Tensile adhesion testing apparatus; (b) different specimen sizes

The author used protocol one from ASTM D4541 and tested the specimens by fracturing or separating them from the plywood substrate. The ASTM D4541 accepts a result of less than ¼ epoxy failure (epoxy is used to adhere the loading fixture to the flashing’s top sheet). However, this study only reported results where 100% adhesive failure occurred. Figure 2.3 illustrates the difference between epoxy failure and 100% adhesive failure.

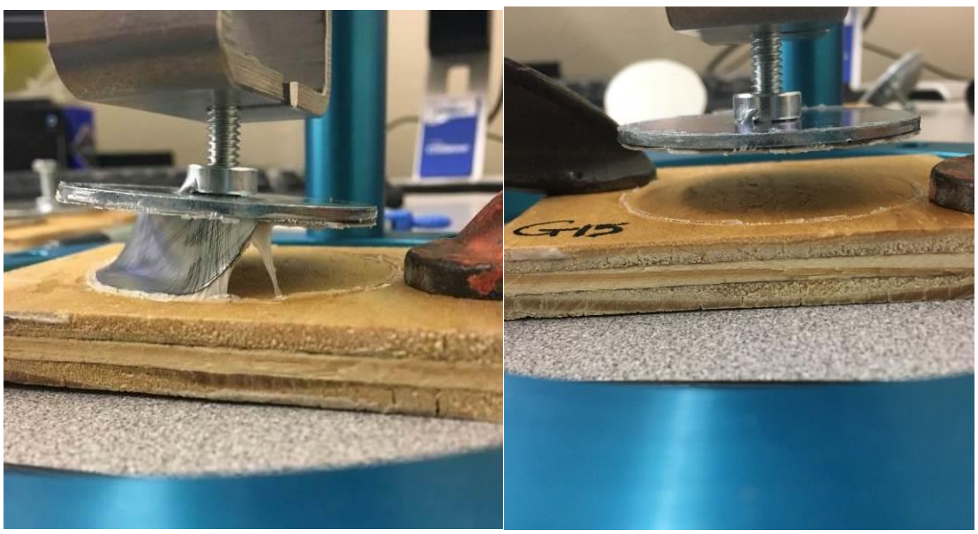


Figure 2.3: Epoxy failure vs. 100% adhesive failure

2.4.3 Exposure Test

In addition to adhesion, another primary concern with the use of adhered products is their reduction in durability after extended environmental exposure. It has been shown that significant differences occur in the performance of tape products after thermal aging (Katsaros 2005). However, the performance of a product that is not stored properly has not been examined. This situation occurs in many small projects where flashing products are carried from one job site to another. To simulate this scenario the specimens of the exposure test were applied in two rounds (Figure 2.4). The first round was applied in November 2016, while the materials used for the second round were stored in an uninsulated shed and applied six months later in May 2017. Visual observations and images of the specimens were recorded on a monthly basis to determine the failure modes and variations in the performance of products.

Figure 2.4: Exposure test (first-round specimens are shown on the left)

2.5 Test Results and Discussion

2.5.1 Shear Adhesion Test

The test results and discussion presented herein emphasize the effects of temperature on the durability of tape and similar self-adhered flashing products. Figure 2.5 shows the time-to-failure vs. mean ambient temperature at which the specimens were exposed upon failing. The results are generated with over 500 specimens subjected to every combination of adhesive and substrate.

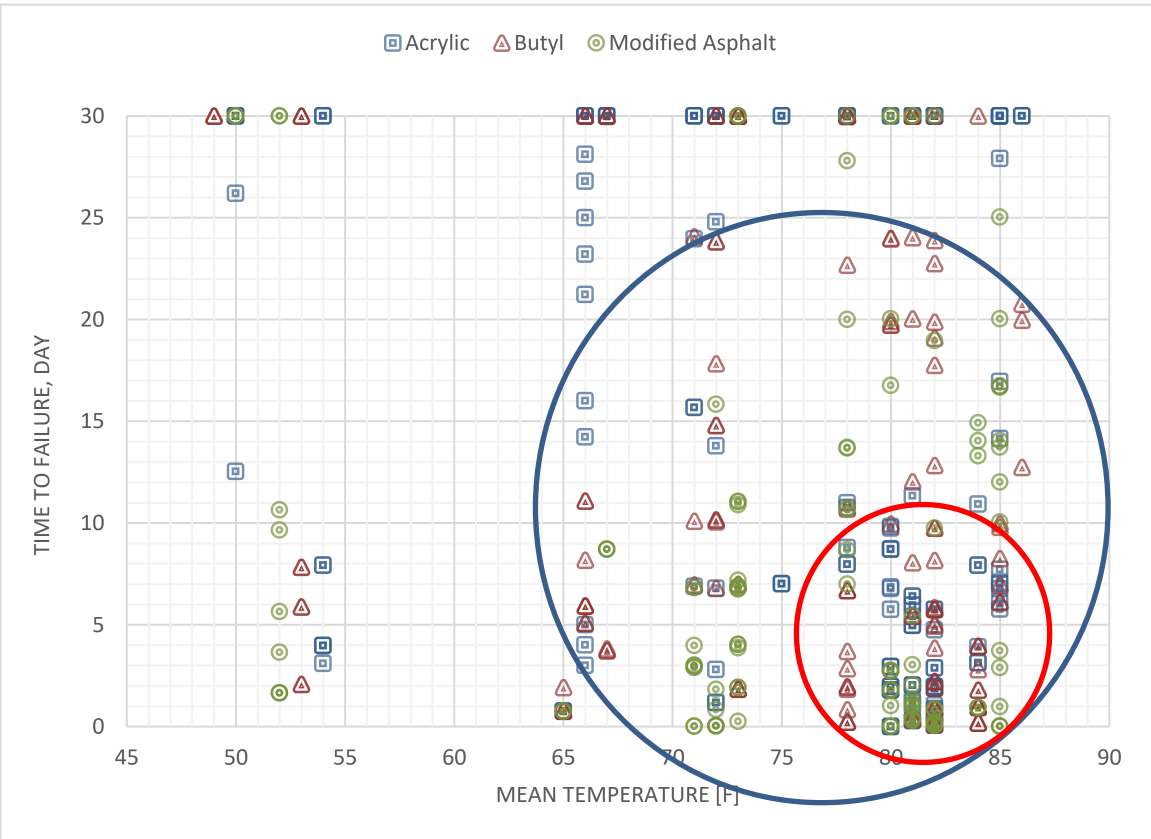


Figure 2.5: Time-to-failure vs. mean ambient temperature of tape specimens in shear adhesion test. Failures are concentrated in the blue circle and even more so in the red circle.

Most of the data points cluster within the blue circle and even more so in the red circle. These results suggest that prolonged exposure to high temperatures reduces the service life of the tape products regardless of the adhesive and substrate used.

To better characterize the behavior of tapes versus exposed temperature, the temperature was normalized into three categories, “hot” (75F to 95F), “average” (55F to 75F), and “cold” (40F to 55F) (Figure 2.6). These categories were specifically assigned for Austin, Texas, where the “average” temperature range often pertains for six months. The normalization of temperature was also established to facilitate further analysis. The vertical bars in Figure 2.6 show the standard deviation of temperature within those months. Generally, the exposure temperature for each specimen could be easily assigned according to Figure 2.6. However, for those specimens that were exposed and which failed in a month on the boundary, their exposure temperature was assigned based on the half of the month in which they were exposed and failed. For instance, the exposure temperature of a specimen was assigned as “cold” if it was exposed and failed in the first half of January 2017, but “average” if it was exposed and failed in the second half.

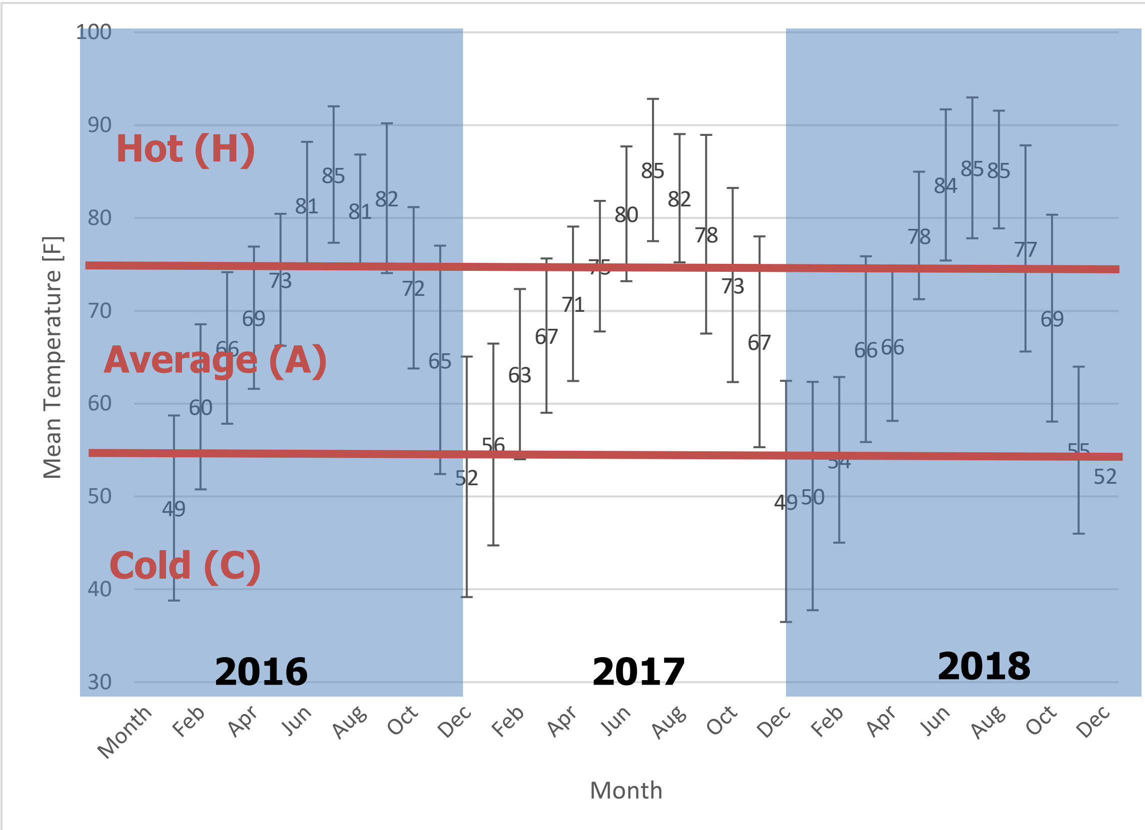


Figure 2.6: Normalization of the exposure temperature. Average temperature (55F-75F) lasts for six months in Austin, TX.

After the exposure temperature was normalized, the adhesives were plotted against their time-to-failure within the three temperature categories (Figure 2.7). This result again proves that exposing the tapes to high temperatures reduces their service life, especially for products consisting of modified asphalt and butyl adhesives. At all temperatures, modified asphalt products seem to be less durable than their competitors; however, they are the most common self-adhered flashing products thanks to their relatively low cost. While butyl performs better than modified asphalt, acrylic is the best performer at all temperature ranges and shows strong resistance to heat damage.

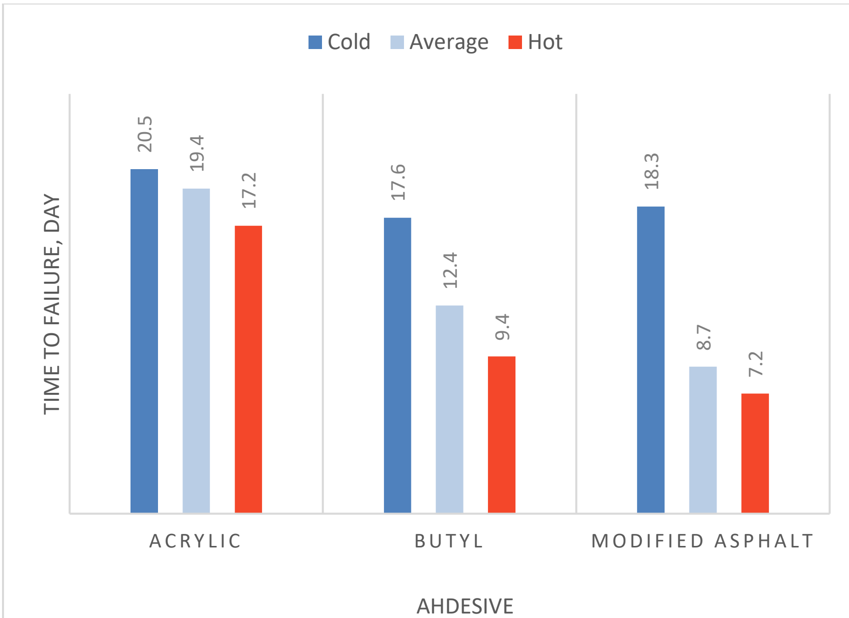


Figure 2.7: Adhesives vs. time-to-failure with normalized exposure temperature

2.5.2 Adhesive vs. Tensile Adhesion

Many tapes and flashing manufacturers adopt ASTM D4541 to determine the tensile adhesion for their products. The results produced from testing 17 products at a one revolution per minute (RPM) loading rate shows that only three products passed the ABAA tensile adhesion requirement (Figure 2.8).

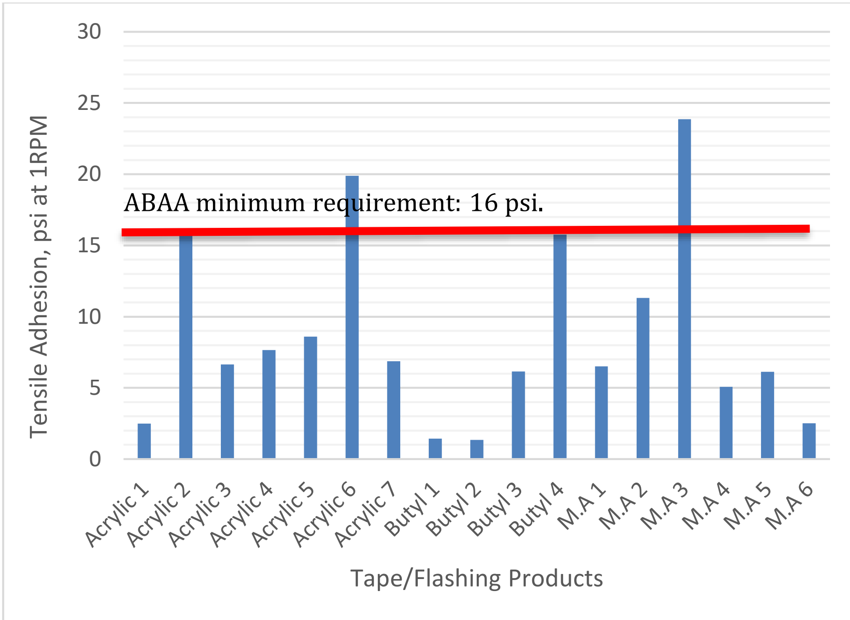


Figure 2.8: Tensile adhesion of tape and flashing products when tested at 1 RPM

However, the tensile adhesion corresponding to various loading rates is not a unique value and is a growing problem faced by many fields. The results shown in Figure 2.9 prove that tape testing is certainly not an exception. The tensile adhesion of the product Butyl 3 can be altered from 6 psi to 26 psi by increasing the loading rate. Essentially, this product could easily pass the 16 psi requirement from ABAA due to this loophole in the code. The change from 6 psi to 26 psi is a huge jump from unqualified to qualified ABAA approval. Naturally, the tape manufacturer would pick the highest value with which to advertise their product, even though it may not necessarily reflect the product's actual performance. The D4541 standard was originally established to measure the tensile strength of coatings that can reach hundreds of psi, far more than that of flashings. This study shows that there is an urgent need to develop a new standard specifically for tapes and flashings; currently, any products are able to pass the current requirements regardless of their performance.

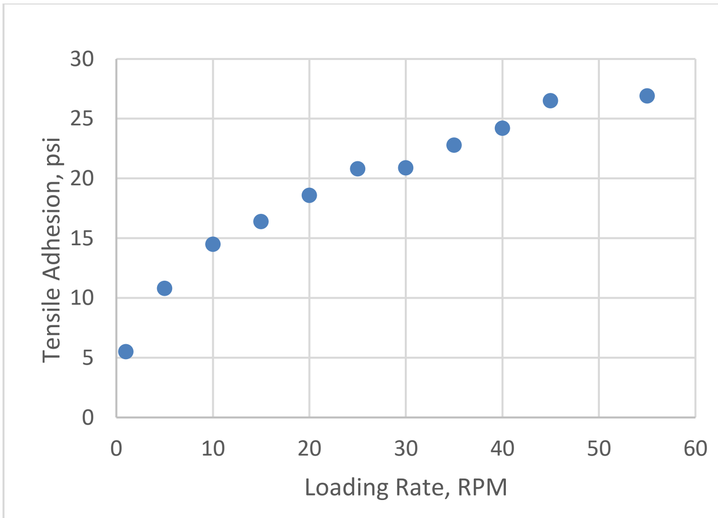


Figure 2.9 Tensile adhesion at various loading rates for the product Butyl 3

2.5.3 Exposure Test

In parallel to the shear and tensile adhesion testing, a qualitative test was conducted using long strips of tapes installed on an exposed proprietary OSB sheathing with an integrated water-resistive barrier to determine how unloaded tapes fail over an extended period. Consolidating two years of observation and image data, it can be seen that the top sheet material (facer) also influences the product performance. The film facer has a tendency to become brittle, to pucker, deform, and curl back after months of exposure depending on the top sheet materials (Figure 2.10). For modified asphalt products this curling action of the facer may also pull the adhesive from the substrate, creating a potential route for moisture infiltration. In contrast, nonwoven composite laminates and aluminum foil facers are more dimensionally stable. After more than two years of exposure the aluminum foil facer appears to be the most durable material. However, specifiers should be careful when choosing this material because of its limitations in transferring moisture vapor.

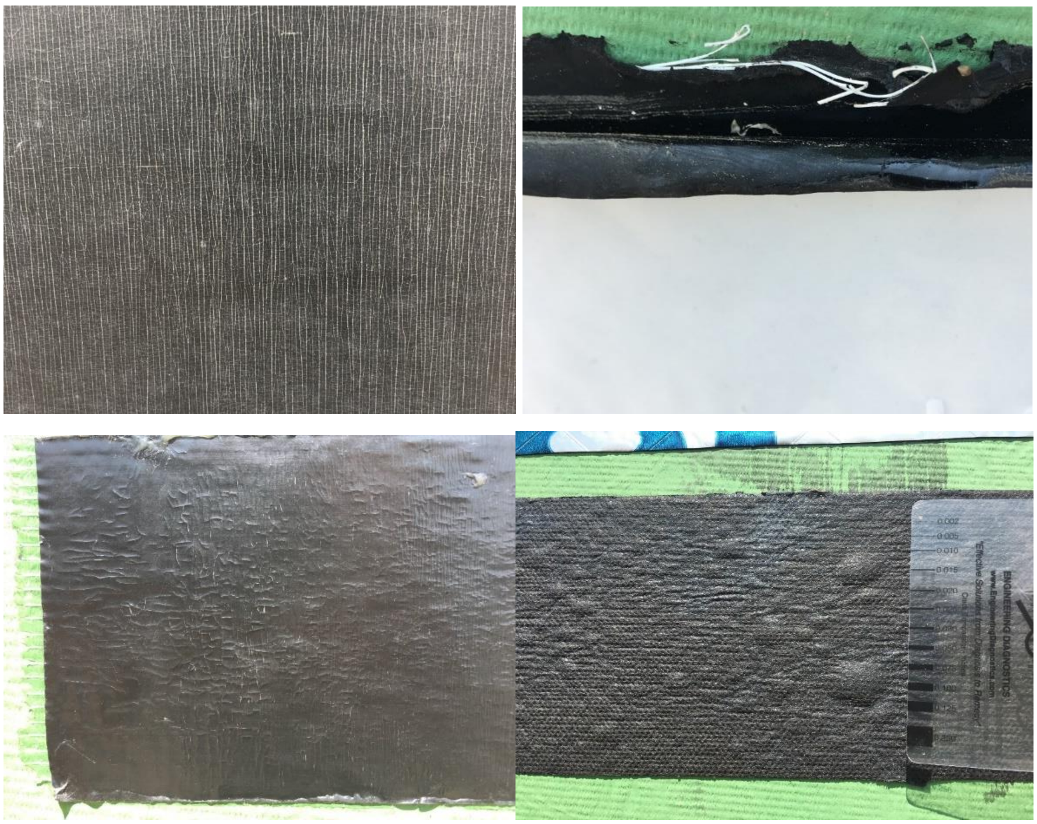


Figure 2.10: Failure modes of top sheet materials

It is common to see that flashing products are not properly cared for during construction. This test proves that proper storage is crucial for flashing products. Figure 2.11 shows failures that occurred consistently on the same specimens installed six months apart. The materials on the right side were stored in an uninsulated shed to simulate inadequate storage. In some cases, failures on these specimens were even more severe. In addition to choosing the correct product and closely following the manufacturer's guidance, the product must be handled with care in order to ensure the overall durability of the project.

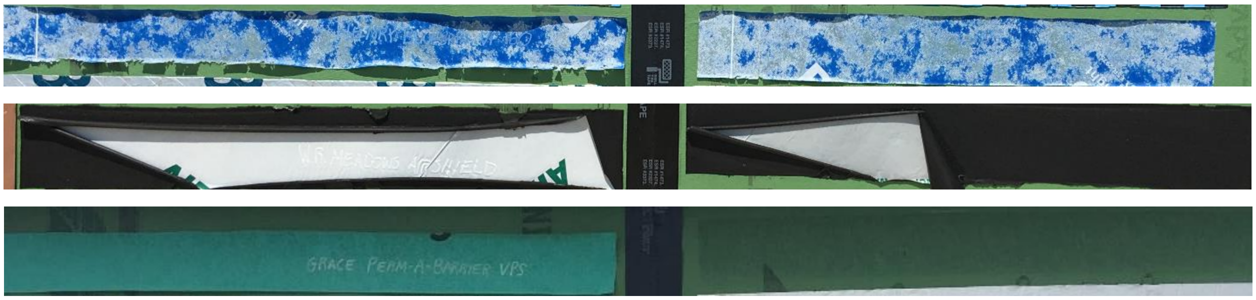


Figure 2.11: Consistent failures occurred on two sets of specimens that were installed six months apart

2.6 Results Summary of Tape/Self-Adhered Flashing Testing

This study explores the behaviors of tape and flashing products under various temperature ranges and exposure periods, in conjunction with the current industry adhesion requirements. The key point resulting from this study is that the durability of tape and flashing systems requires collaboration from all parties. The designer must consider every factor of a project including application, substrate, and the temperature at which the product will be applied and exposed in order to select an appropriate product. The contractor must follow the product literature and establish a proper plan to carry the product. Moreover, the manufacturer must truthfully advertise product performance, and test results and installation guidance must be thorough, accurate, and clear. Finally, the authority must establish standards that reflect the field conditions and requirements that promote product durability.

Chapter 3: Exterior Plaster Mixtures

3.1 Problems Description

The U.S. Census Bureau estimated that all stucco-like siding represented 19 to 22% of the total US exterior siding market in 2016. This translates to the stucco (exterior plaster) industry making over two billion dollars in annual sales for the siding industry. While stucco has a long history of use, limited data is available to fully understand its material properties, especially when it comes to forensic investigation, because stucco failures can be attributed to a wide range of issues. According to the Technical Services Information Bureau, stucco membrane can be subjected to abnormally high stresses in the first few months after application from various sources such as shrinkage stress, ground settlement, seismic and thermal movements, dead and live loads, structural framing movements, and vibrations from heavy equipment and construction.

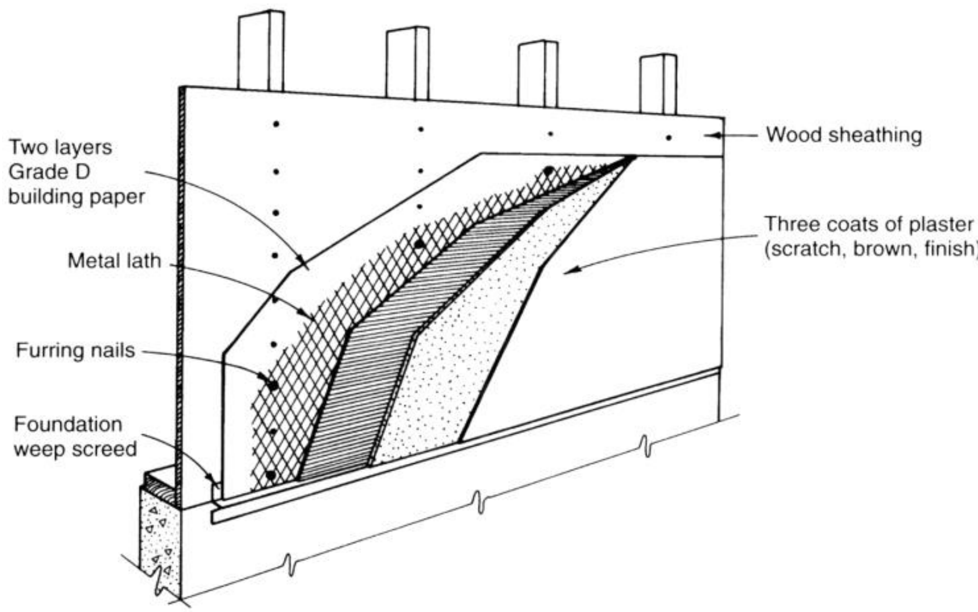


Figure 3.1: Layout of a generic stucco membrane (Image courtesy of Portland Cement Association)

Of these factors, specifiers only have control over the product and methods of construction used (i.e., control joint spacing and curing). Since stucco shrinkage depends on temperature, humidity, and curing methods, stucco manufacturers are not able to publish shrinkage properties. Therefore, to design control joint spacing, specifiers must rely solely on the specifications provided in the stucco manual based on ASTM C1063, *Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster*. Standard C1063 specifies that the joint spacing should be less than 18 feet. Each stucco panel should not exceed 144 ft^2 on vertical applications, while for curves or angular sections no panel should exceed 100 ft^2. The length-to-width ratio of a panel should not exceed 2.5.

Regarding material properties, many stucco manufacturers publish data on the compressive strength only, if any data at all. This is not sufficient to understand the expected movement of the products. Furthermore, the same stucco mix can exhibit very different behavior depending on the environment to which it is exposed. This report aims to determine the mechanical properties and coefficient of thermal expansion (CTE) of exterior plaster, which is the most important component that governs the behavior of a stucco membrane. Understanding the variability of the CTE of stucco can also assist a specifier in making an informed decision when selecting the appropriate product or siding for a given project.

3.2 Testing Sample Description

3.2.1 Types of Plaster Mixtures

There are several types of stucco installations, which can generally be categorized into two groups: ASTM (traditional stucco) and pre-blended mixtures. The most traditional and popular of these types is the traditional 3-coat stucco, in which stucco is applied in three coats (scratch, brown, and finish) over metal reinforcement (Figure 3.1). The scratch coat is applied first to provide a strong base for the system. This coat embedded in metal lath, which strengthens and secures the coat. The brown coat is applied next, followed by the finish coat, which creates a decorative texture on the wall surface. The proportion of cement, lime, sand, and water of traditional 3-coat stucco are specified in ASTM C926-18b, *Standard Specification for Application of Portland Cement-Based Plaster*. In a pre-blended mix, the product itself often includes all of the components except for water, which is added at the job site. The material composition of a pre-blended mixture is more variable. Depending on the manufacturer, a pre-blended mix may also include supplementary cementitious materials, fibers, water-reducing agent, and shrinkage-reducing agent (SRA). It is questioned whether SRA can lead to premature failure of sheathing by reducing the surface tension of building wraps, leading to moisture infiltration. This study is currently in the development phase and will be included in the near future at the Durability Lab.

3.2.2 Mixtures and Specimens in the Mechanical Properties Study

Five pre-blended mixes were selected to study the mechanical properties of stuccos. Seven 4” x 8” cylinder specimens were casted for each plaster mixture in compliance with the manufacturer's recommendation. The mixture proportion of a pre-blended product is often associated with the weight of material per bag. For instance, mix PB2 requires one gallon of water for every 80 lb bag. Some products also require plaster sand and water to be added when mixing. The material proportions as specified by the manufacturers and ASTM C926 are shown in Table 3.1.

Table 3.1: Mixture proportion of plaster mixtures

Mixture ID	Type	Portland Cement Type I	Masonry Cement	Lime	#4 Sand	Water
1	C926 Type C	1			3	1/2
2	C926 Type CL	1		1	6	1/2
3	C926 Type M		1		3	1/2
4	C926 Type CM	1	1		6	1/2
5	C926 Type MS		1		3	1/2
7	PB1	1 pre-blend of sand and proprietary plaster : 1/8 water				
6	PB2	1 pre-blend of sand and proprietary plaster : 1/9 water				
7	PB3	1 proprietary cement : 3 plaster sand : 3/7 water				
8	PB4	1 proprietary cement : 5/2 plaster sand : 2/7 water				
9	PB5	1 pre-blend of sand and proprietary plaster : 1/6 water				

After the mixtures had set, the specimens were moist cured in 100% humidity conditions by placing wet burlaps on top of them. To simulate the curing process for stucco installation the specimens were removed from the molds after 24 hours of burlap curing and placed in a fog curing room for another 48 hours (Figure 3.2). The specimens were then air cured for the following 25 days before being tested at an age of 28 days.

Figure 3.2: Cylinder specimens in the fog curing room

3.2.3 Mixtures and Specimens used in the Coefficient of Thermal Expansion Study

Eight different plaster mixes – five ASTM and three pre-blended – were included in the CTE study. Each contained three 1” x 1” x 10” prisms casted in compliance with ASTM C305, *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*. The specimens used in this CTE study were casted in 2016 and 2017 for a shrinkage study by affiliates of the Durability Lab (Figure 3.3). The specimens were then stored in an environmental chamber maintained at 70 degrees Fahrenheit and 50% humidity.

In the field, water is typically applied to yield a workable mixture. Since no test method is established to measure the workability of stucco, a constant proportion of water was used to yield a seemingly workable blend for all mixtures. The proportion of water chosen for testing was ½ of the cementitious materials by volume. The complete aggregate to cementitious material to water ratio was 3:1:1/2. Materials for batching were obtained from a local supplier and consisted of type I Portland cement, type N masonry cement, type S masonry cement, Austin White Lime, and a #4 sand.

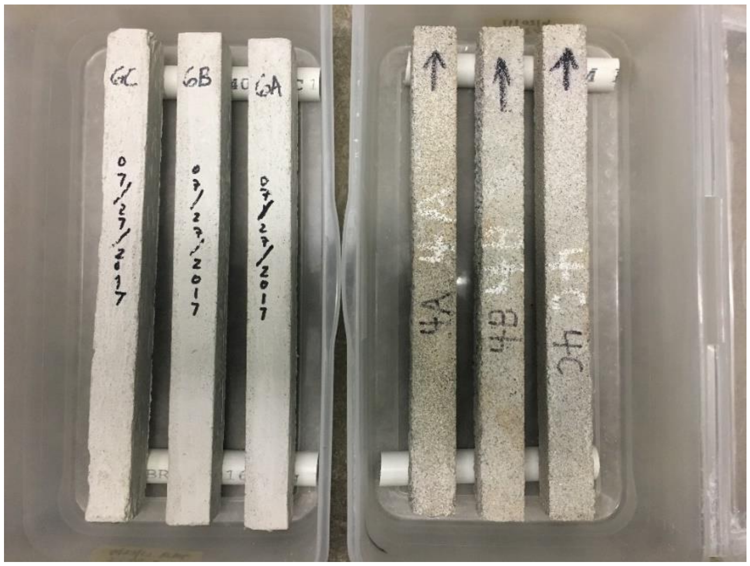


Figure 3.3: Prism specimens used in the CTE study

It is crucial for the specimens used in this CTE study to have experienced all of the movement caused by autogenous shrinkage and plastic shrinkage. Otherwise the test result could be jeopardized, since stucco typically has a relatively high water to cement ratio, meaning that plaster is significantly affected by autogenous and plastic shrinkage. In the fresh stage, autogenous shrinkage happens as water is rapidly drawn to the hydration process of cement. Plastic shrinkage occurs due to water evaporation. Length measurements of the specimens were monitored over three days to confirm that their movements were stable.

3.3 TESTING METHODOLOGY

3.3.1 Mechanical Properties

Three ASTM standards were adopted to determine the mechanical properties of stuccos. All seven cylinders were tested until failure at 28 days of age. A tight procedure was developed to obtain three data points for each test using seven specimens. First, one specimen was tested until failure to obtain the compressive strength (f'c) as per ASTM C1231, *Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Cylindrical Concrete Specimens*. The next three specimens were loaded to 0.4 f'c while recording the displacement to obtain the modulus of elasticity as per ASTM C469, *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. These specimens were then tested again as per ASTM C1231 to obtain the compressive strength. The last three specimens underwent ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. The tensile strength (fsp) was found using the following expression: fsp = 2P(πDL), where P is the applied load in the split cylinder test, D is the diameter of the cylinder, and L is the length of the cylinder.

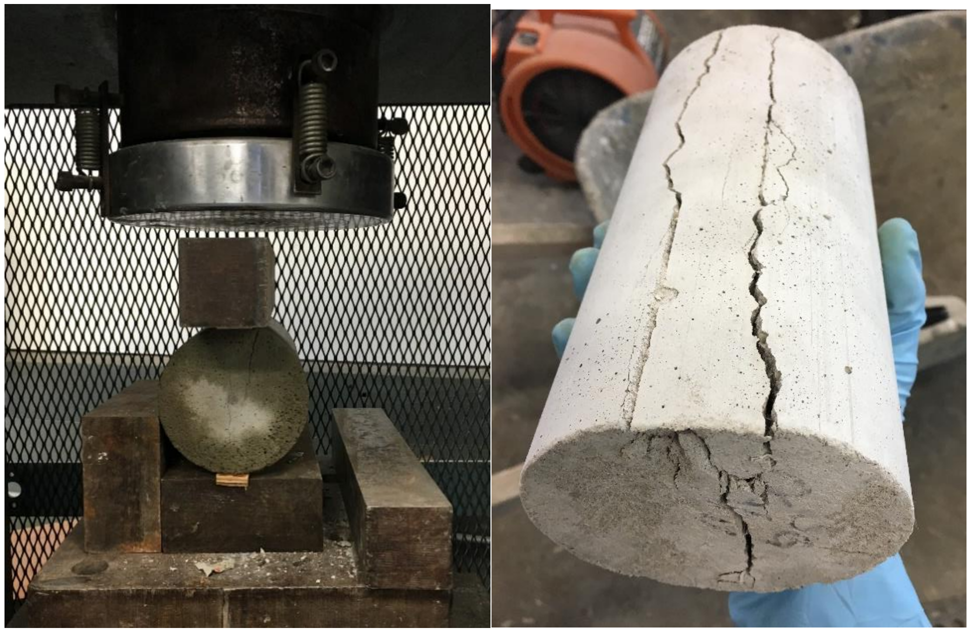


Figure 3.4 Testing apparatus for the ASTM C496 split tensile test

Regarding the modulus of elasticity, it was unknown whether plaster behaves linearly in the 0 to 0.4 f’c region. To investigate this, the stress–strain response of the first mixture was recorded every 0.00060” of displacement on the strain gauge. The strain was found using the following expression: longitudinal strain = measured displacement / 2 x gauge length, where the gauge length is 5.3 in. Base on the stress–strain response (Figure 3.5), plaster was found to behave elastically within the 0.4 f’c region.

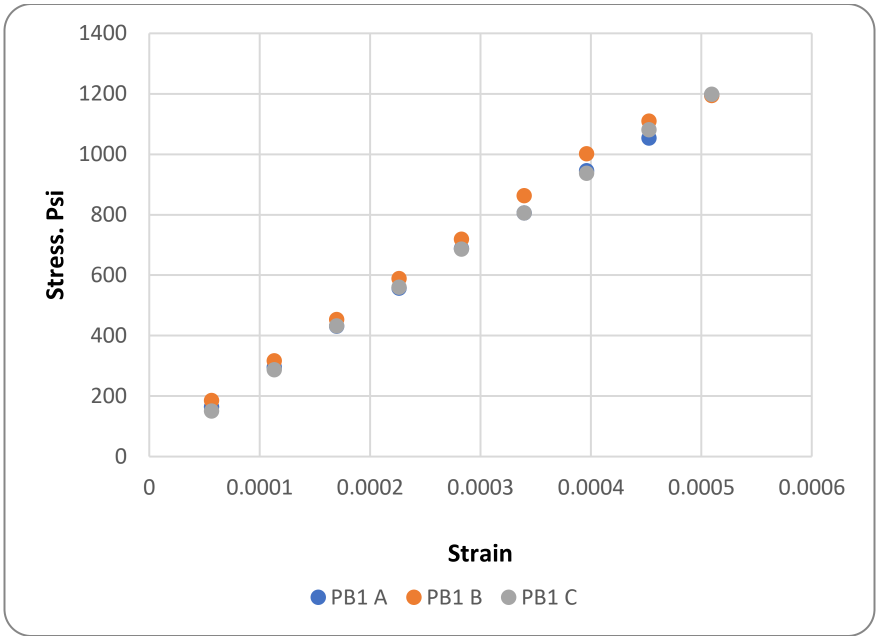


Figure 3.5: Stress–strain relationship of the pre-blended mix PB1

According to this result, the test procedure for the modulus of elasticity can be simplified by using two specific data points. The modulus of elasticity in this case was:

$$\text{Modulus of elasticity, E} = \frac{f_{c2} - f_{c1}}{\varepsilon_{c2} - \varepsilon_{c1}}$$

where f_{c2} is the stress corresponding to 40% of the compressive strength of plaster,

f_{c1} is the stress corresponding to longitudinal strain ε_{c1},

ε_{c1} is 0.000050 in./in., and

ε_{c2} is the longitudinal strain corresponding to stress f_{c2}.

Figure 3.6: Testing apparatus used to determine the modulus of elasticity

3.3.2 Coefficient of Thermal Expansion

It is of interest to evaluate the variability of the CTE of plaster in different moisture conditions. The movements of eight stucco mixes corresponding to a range of temperatures were monitored using testing apparatus in compliance with ASTM C596, *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement*. Testing was performed in two rounds, under dry and wet moisture conditions. The wet moisture condition was simulated by submerging the specimens under three inches of distilled water. During each round the specimens were exposed to a temperature sequence of 70, 100, 120, 140, and 70 F. Three specimens of each mix were stored in a closed container to prevent the effects of humidity existing in the environmental chamber. The specimens were exposed to each temperature for two days before taking the length measurement.

Figure 3.7: Testing apparatus to determine the length changes of plaster

3.4 RESULTS AND DISCUSSION

3.4.1 Mechanical Properties and Analytical Modeling

The mechanical properties of the ASTM and pre-blended mixes are summarized in Table 3.2.

Table 3.2: Mechanical properties of exterior plaster mixtures

Product Description		Compressive Strength [psi]	Tensile Strength [psi]	Elastic Modulus [psi]	Tensile Cracking Strain [%]
Pre-blended Mixes	PB 1	2883	308	2.42E+06	0.0127
	PB 2	4019	321	2.37E+06	0.0136
	PB 3	4061	495	2.75E+06	0.0180
	PB 4	4026	469	2.37E+06	0.0198
	PB 5	2504	289	2.08E+06	0.0105
ASTM C926 Mixes	Type C	1289	-	-	-
	Type CL	684	-	-	-
	Type M	1150	-	-	-
	Type CM	1424	-	-	-
	Type MS	1132	-	-	-

The tensile cracking strain of the mixes was calculated by dividing the tensile strength by the corresponding elastic modulus. This method does not yield an accurate result when calculating under compression, as exterior plaster is a composite material and behaves non-elastically approaching failure. However, it was confirmed that within the 0.4 f'c region the stress−strain curve was linear (Figure). Therefore, the cracking strains in tension presented herein are valid.

Furthermore, it can be seen that the pre-blended mixes have far higher compressive strength than the ASTM mixes. The pre-blended mixes can withstand much higher stress during and after construction. Higher compressive strength also translates to higher tensile strength and possibly greater durability. However, stucco is not and has never been intended as a structural component, reaching a compressive strength of 4000 psi such as the mixes PB 2, 3, and 4 might be unnecessary.

In term of fixing stucco failure, it is very important to maintain the homogeneity of the membrane. As such, it is necessary to determine the mechanical properties of the product brand of existing plaster. Even knowing whether it is an ASTM or pre-blended mix can be useful as test results have shown that they have drastically different properties. Choosing a pre-blended mixture to patch an ASTM mix might exacerbate the issue since their movements are not similar leading to internal stresses. As a result, the stucco wall may crack, spall, or even delaminate as a form of stress relief.

Several ACI 318 models to predict the tensile strength and modulus of elasticity were also included in the study. The results are presented in Table 3.3.

- Tensile strength = 6 x $\sqrt{f'c}$ (psi)
- Modulus of elasticity (1) = 57,000 x $\sqrt{f'c}$ (psi)
- Modulus of elasticity (2) = 33 x $145^{1.5}$ x $\sqrt{f'c}$, in which 145 pcf denotes concrete density

Table 3.3: Comparison of predicted tensile strength and modulus of elasticity values vs. test results

Product	**Modulus of Elasticity (1)**		**Modulus of Elasticity (2)**		**Tensile Strength**	
	E, psi	**Predicted/ Measured**	**E, psi**	**Predicted/ Measured**	**Tensile, psi**	**Predicted/ Measured**
PB 1	3.06E+06	1.3	3.09E+06	1.3	322	1.0
PB 2	3.61E+06	1.5	3.65E+06	1.5	380	1.2
PB 3	3.63E+06	1.3	3.67E+06	1.3	382	0.8
PB 4	3.62E+06	1.5	3.66E+06	1.5	381	0.8
PB 5	2.85E+06	1.4	2.88E+06	1.4	300	1.0

It can be seen that the predicted modulus values for both models (1) and (2) were not accurate, while the predicted tensile strength values agreed fairly well with the test results. For the modulus of elasticity, another model (3) was developed by integrating the model (2) with the density of plaster in an attempt to better characterize its properties. After calibrating with seven specimens of the pre-blended mix PB5, the density of plaster was found to be 122 pcf. This is consistent with the density of mortar, which is about 120 pcf. The results in Table 3.4 prove that this model is able to predict the modulus of a given plaster mixture from its compressive strength.

Modulus of elasticity (3) = $33 \times 122^{1.5} \times \sqrt{f'c}$ (psi), where 122 pcf denotes the density of exterior plaster

Table 3.4: Comparison of predicted modulus (model 3) vs. test result

Products	**E measured, psi**	**E predicted, psi (Model 3)**	**Predicted/Measured**
PB 1	2.42E+06	2.39E+06	0.99
PB 2	2.37E+06	2.82E+06	1.19
PB 3	2.75E+06	2.83E+06	1.03
PB 4	2.37E+06	2.82E+06	1.19
PB 5	2.08E+06	2.23E+06	1.07

3.4.2 Coefficient of Thermal Expansion

Length measurements were taken two days after exposing specimens at a certain temperature using a length comparator (Figure 3.7). The CTE of the plaster mixtures were determined by the following two steps:

- Strain at temperature T, $Strain_T$ (in/in) = $\frac{L_T - L_{70}}{L_{70}}$, where L_T is comparator reading at temperature T
- CTE (in/in/F) = $\frac{Strain_T}{T-70}$

The CTE of each mix is the mean value calculated from the temperature ranges of 70–100 F, 70–125 F, and 70–140 F. For the pre-blended mixtures exposed in dry conditions, the comparator readings at 100 F were actually lower than those at 70 F. This phenomenon was attributed to the free moisture in the environmental chamber at 70 F, which is maintained at 50% humidity. As a result, the specimens lost moisture and shrank when they were exposed at 100 F. The shrinkage caused by evaporated moisture can be seen to dominate the thermal expansion. To avoid this issue, the CTE of the pre-blended mixtures in dry conditions were weighted using temperature ranges of 100–125 F, and 100–140 F. Table 3.5 shows the compressive strength and CTE of each mixture in wet and dry moisture conditions.

Table 3.5: The CTE vs. compressive strength of exterior plaster mixtures

Mix ID	CTE, x10^-6 [in/in/F]		Compressive Strength, psi
	Submerged	Dry	
C926 Type C	7.0	3.3	1289
C926 Type CL	6.7	3.4	684
C926 Type M	6.6	4.3	1150
C926 Type CM	6.5	4.3	1424
C926 Type MS	6.2	3.5	1132
PB2	7.0	3.8	4019
PB3	6.8	4.6	4061
PB4	6.5	4.0	4026

Figure 3.8 shows a plot of compressive strength and CTE of the mixtures in both moisture conditions. When considering the effects of compressive strength, it is notable that while the pre-blended mixes exhibit much greater strength compared to the ASTM mixes, their CTE in both moisture conditions appears to be similar. The compressive strength of a cement-based mixture is directly linked to its water to cement ratio and aggregate content. From the results it can be concluded that the mixture proportion of a plaster mixture does not really affect its CTE. However, it is apparent that the moisture conditions greatly affect the CTE of plaster mixtures. The CTE in wet conditions were up to twice as high compared to those in the dry condition, depending on the mixture. This can be attributed to the expansion of water within the pore structure. Furthermore, the result suggests that stucco moves more in areas with high humidity and rainfall. While it is not apparent, the moisture condition seems to have a slightly greater impact on the pre-blended mixes than the ASTM mixes.

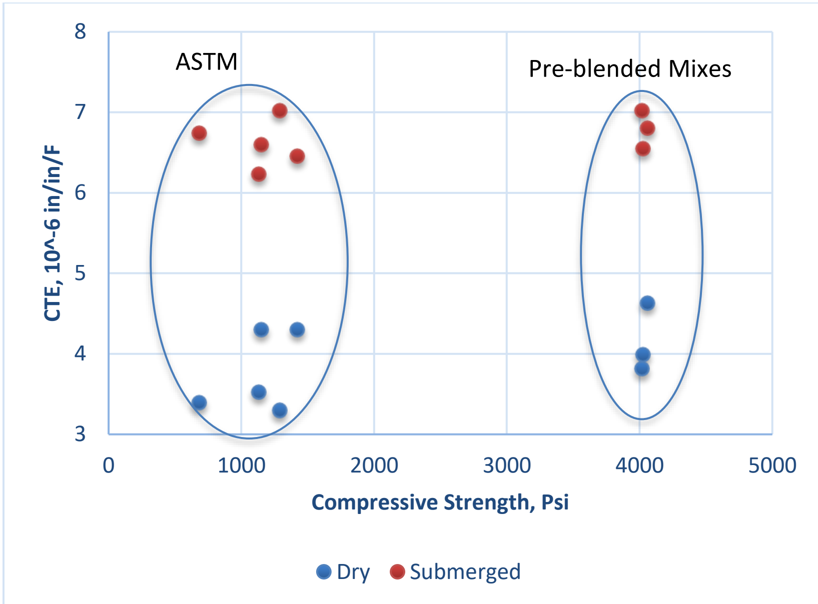


Figure 3.8: Plot of the CTE vs. compressive strength of the ASTM and Preblended exterior plaster mixture

3.5 Results Summary of Exterior Plaster Testing

A crack formed in cement plaster stucco is a form of stress relief when the restrained shrinkage stress exceeds the tensile strength of the plaster. More often than not, pinpointing the precise source of stress that caused cracking is impossible since stresses in stucco membrane result from various sources. Generally, stress in stucco can be placed into one of two categories: (1) stress within the plaster membrane that is induced by shrinkage and thermal movements, and (2) outside stress placed upon the plaster membrane such as dead and live loads, seismic conditions, and structural framing movement. While the study does not attempt to solve these problems, it provides investigators with the tools to assess the problems associated with the mechanical properties of plaster (i.e., compressive strength, tensile strength, modulus of elasticity, and cracking strain) in addition to the considered physical property (CTE). Accordingly, investigators can determine the tensile strength and modulus of elasticity of a given plaster mixture and compare these values with the in-situ loading conditions using the models established in this study. Designers must take both mechanical and physical properties of a plaster mixture into account when specifying a durable stucco mix intended to last for the design life of a building. Furthermore, stucco detailing, the layout of control joints, and moist cure after placing plaster must be specified and should follow industry standards in order to ensure the long-term durability of a stucco cladding.

Chapter 4: Water Repellents

4.1. Problems Description

Various remedial methods can be taken to prevent water infiltration into a building envelope when the inner water-resistive barrier (WRB) fails or is not present. The most direct means to do so is probably to remove the existing cladding and to replace or install a WRB, which is cost-prohibitive and time-consuming. An alternative method to reduce water infiltration is to apply an exterior coating directly to the cladding. Typically, an elastomeric coating is used as a water-repellent membrane for exterior plaster and concrete masonry units. These coatings have a color and texture of their own; however, clear penetrating water repellents are also available which preserve the aesthetic value of the cladding underneath.

The design life of water-repellent treatments is usually considered to be 10 years or more. However, limited data is available to demonstrate which products can handle long-term weathering, especially concerning the in-situ durability of water-repellent treatments. Nonetheless, the success of a treatment does not depend on the treatment alone (i.e., the product and its application method) but also the substrate to which it is applied (Moreau 2008). To remedy this lack of knowledge, 32 different water repellents from eight different manufactures were selected for long-term testing. This study summarizes the performance evaluation of these products over the course of a three-year exposure period.

4.2 TESTING SAMPLE DESCRIPTION

4.2.1 TYPES OF WATER REPELLENTS

The types of water repellents and application methods have been summarized in previous publications from this project (Gagnon 2016). In brief, two broad are used to classify the general term "water repellents." Film formers create a continuous water-resistant layer on the surface of the substrate, while penetrants change the capillary force in pores from positive to negative. Film formers typically consist of relatively large molecules compared to those of penetrants, which allows the film membrane to bridge hairline cracks in the substrate. Film formers typically consist of acrylics, urethanes, stearates or mineral waxes. Penetrants are used more commonly because they are generally more durable and do not impose a major aesthetic change on the substrate. Due to the smaller molecular structure, they can penetrate into the pores of the substrate and form a "semi-permeable" membrane that prevents water from infiltrating inwards and allows the substrate to breathe. There are several types of penetrants including silanes, siloxanes, silicates, siliconates, silicone resin, RTV (room temperature vulcanizing) silicone rubber, and blends of the above. Water-repellent products typically consist of a carrier (solvent or other liquid) and a resin (active content).

This study mainly focused on penetrants due to their superiority over film formers in terms of durability. Of the 32 water-repellent products, two were film formers and 30 were penetrants. Four specimens were created for each product: one as a file specimen to be kept indoors, and three to be exposed outside. The outdoor specimens were exposed at an orientation of maximum UV exposure at the Durability Lab.

4.2.2 Substrate – Terra Cotta Saucer

To evaluate the water repellency of the treatments a suitable substrate must be carefully chosen. In previous research at the Durability Lab conducted from 2013 to 2016, terra cotta substrate was found to be the most suitable candidate for three reasons. Firstly, terra cotta has a similar absorption potential and pore structure to clay brick masonry, which is the primary substrate of vertical water-repellent treatments. Secondly, results from the water absorption test indicated that the terra cotta saucers were practically identical from one saucer to another. The average water absorption by weight determined for 12 specimens was 10.3%, which is similar to that of clay brick. The standard deviation of the test was 0.33%. Finally, the terra cotta saucers were of a manageable size with a diameter of four inches, allowing multiple specimens to be created and tested simultaneously.

4.3 TESTING METHODOLOGY

Three test were selected based on the most common test methods in practice and recommendation from the Sealant, Waterproofing, and Restoration (SWR) Institute. Each test listed in this section was completed initially at fourteen days after the treatment and at six-month intervals to determine the effect of outdoor weathering and aging on the products' performance.

4.3.1 Surface Beading (Beading Ability) Test

The surface beading test is a qualitative test that evaluates the repellency of a treatment by misting water on the treated surface and recording its tendency to bead. Significant surface beading was initially observed on several products. After outdoor weathering, surface beading decreased exponentially. While surface beading is a good initial test to determine the level of water repellency and to check for any missing application, it was unclear how the test related to the effectiveness of a water-repellent treatment.

Figure 4.1: Different surface beading tendencies were noted after a rainfall event at the outdoor exposure rack at the Durability Lab.

Surface beading can be graded based on the contact angle between the water droplet and treated surface, using different grading scales. However, this process is often performed visually and can be biased because each individual might interpret a contact angle differently. In addition, when using the grading system it can be challenging to evaluate a treatment on a non-horizontal surface since the contact angle may be distorted or water droplets may run off. To avoid misleading results, surface beading in this study was normalized by numerically assigning “2” when the entire surface beads water, “1” when beadings are partially observed, and “0” when no beading takes place (Figure 4.2).

The normalized surface beading was finally plotted against the exposure time and treatment effectiveness to determine the role of beading ability in the long-term performance of water repellents.

Figure 4.2: Normalization of beading ability

4.3.2 RILEM Tube Test

Another common method applied to measure the effectiveness of a water-repellent treatment in the field is the RILEM tube test, in which test tubes use varying water levels to induce hydrostatic pressure equivalent to pressures created by wind-driven rain. The 5 mL RILEM test tubes were fixed to the substrate with the use of putty, and tube tests were performed on one specimen from each product. Readings of water uptake were recorded at 5, 10, 15, and 20 minutes after adding water to the tube. When the water uptake was greater than 0.25 mL after 20 minutes of the test, the test was continued for one hour. Water uptake readings in this case were recorded at 30 and 60 minutes. Figure 4.3 shows the RILEM test apparatus.

Figure 4.3: RILEM tube testing

4.3.3 Water Absorption Test

The water absorption test is the most harsh test and is recommended by the SWR Institute for testing bulk water absorption. All products were submerged in distilled water, with no specimen at a depth of greater than 3 inches (Figure 4.4). At approximately 48 hours each specimen was removed and wiped with a wet rag in order to achieve a saturated-surface-dry condition. Immediately after wiping with the rag, the specimens were weighed to determine their saturated weight and percent absorption.

Five different products validated by the SWR Institute were used in this study. For validation, the SWR Institute requires that manufacturers test the effectiveness of their products' ability to reduce water absorption in accordance with various ASTM standards. Each test method is suitable for a given substrate and has specific requirements for drying and saturation of the substrate. Table 4.1 shows the ASTM test methods required by the SWR Institute and the ASTM C97, a similar test method used for natural stone.

Table 4.1: SWR Institute validation requirements for absorption. (*) Concrete and mortar samples were oven-dried until they reached a constant weight to the nearest 0.1g in any four-hour period

Test Method	Substrate	Drying	Saturation
ASTM C67	Brick	24 hours at 230 F	24 hours
ASTM C140	CMU	24 hours at 230 F	24–28 hours
ASTM D6532	Concrete/mortar	At 176 F (*)	3 days, ¼-inch depth
ASTM C97	Dimension stone	48 hours 140 F	48 hours

Figure 4.4: Water absorption test

4.4 Results and Discussion

4.4.1 Durability of Water-Repellent Treatments

The treatment effectiveness measures the reduction of water absorption and can be calculated as a percentage with the following equations:

$$\text{Percentage effectiveness} = \frac{10.265 - \%absorbtion}{10.265} \text{ x } 100\%$$

$$\text{Percentage absorption} = \frac{Wet\ weight - dry\ weight}{Dry\ weight} \text{ x } 100\%$$

The maximum water absorption by weight of the 12 untreated specimens is 10.265%.

Preliminary analysis indicated that the majority of the products which increased to over 80% effectiveness at 6 months were less than 20% effective during initial testing. Several other products exhibited average increases of over 50% effectiveness between the first and second rounds of testing. Of these products, only one was identified by a manufacturer as requiring at least 28 days of curing. Water-repellent products have various curing times and the lack of this information hinders users' ability to take extra measurements when necessary.

While each water-repellent product behaved differently over time depending on the chemical composition and carrier, the effectiveness of most products follows one of two behaviors. The most common behavior is "good product stays good" – that means if the initial effectiveness is greater than 80%, the water repellency of the products remains excellent over time (Figure 4.5). All of the five products that were validated by the SWR Institute fall into this category. The discrepancy between the file and exposed specimens in this case can be neglected. The product effectiveness appears to slightly decrease two years after application; however, these products still demonstrate outstanding performance considering that the submergence test is rather harsh in comparison to field conditions. After 37 months of weather exposure the average effectiveness of the exposed specimens was 87%, which is similar to that at 14 days. In contrast, the average effectiveness of the file specimens was 92%.

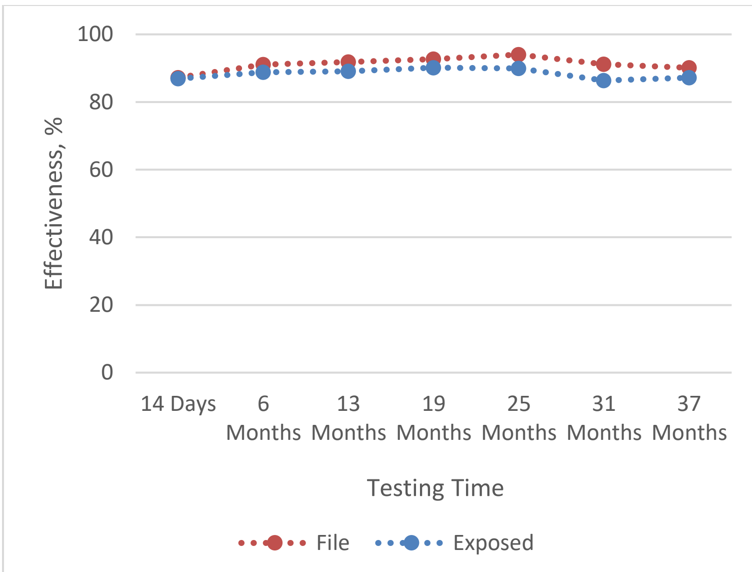


Figure 4.5: Average effectiveness of file vs. exposed specimens of the “good products”

The other major behavior was observed on nine products that initially demonstrated poor performance with an average effectiveness of 13%. From Figure 4.6 it is evident that these “bad products” typically took up to one year to fully cure and were prone to degradation by weathering. The discrepancy in effectiveness between the file and exposed specimens became apparent after 6 months of exposure and subsequently worsened. After 37 months of exposure, the average effectiveness of exposed specimens was 29%. Furthermore, the result was particularly troublesome because the average effectiveness of the file specimens was 83%, demonstrating the opposite performance and providing a false impression of the capability of the products.

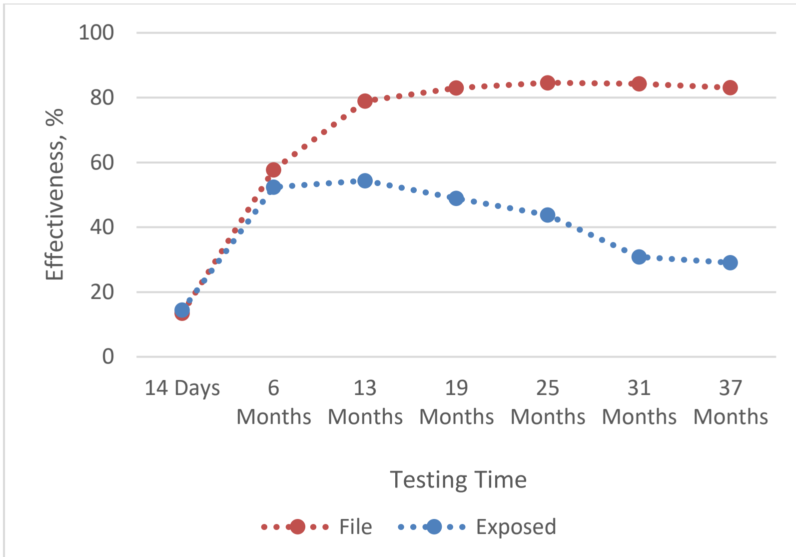


Figure 4.6: Average effectiveness of file vs. exposed specimens of the "bad products"

Overall, the results indicated the inability of the standard specifications and test methods to account for both aging and weathering. Although it might be cost-prohibitive, long-term testing is necessary to assess the actual field performance of a product. Both of the film former products were considered "bad" in this study, and both exhibited poor performance for two likely reasons. First, the water-repellent membrane of the film former was directly exposed to the environment, unlike the penetrants. Second, the film former is typically composed of urethanes, acrylics, or mineral waxes, which tend to degrade under prolonged UV exposure.

The data summarized in Table 4.2 suggests that the label of a "good" product can be attributed to any chemical composition or carrier. However, the results presented herein were consolidated from three years of exposure. There remains much to learn when it comes to durability. Time is the final variable that will provide greater insight into the correlation of the long-term performance and product chemistry. Regarding "bad" products no single case of silane was observed, but they included three hybrids, three silicones, and one fluoropolymer (there were also two additional products whose chemistry was not published). In addition, the majority of these products were water based (seven water vs. two solvent), which suggests that the hastened transition from solvent-based to water-based products carried out to comply with increasingly strict environmental regulations has not yet arrived at a point where their performances are comparable.

Table 4.2: Chemistry and carrier description of the "good" and "bad" products

Description	**Number of Products**	
	"Good" Products	**"Bad" Products**
Chemistry		
Silane	9	0
Silicone	3	3
Hybrid	7	3
Carrier		
Water	11	7
Solvent	9	2

4.4.2 Beading Ability vs. Treatment Effectiveness

The effect of surface beading does not appear to have a positive effect on treatment effectiveness, according to the monitoring of these properties over time. The relationship between surface beading and exposed average effectiveness after 37 months of "good" and "bad" products can be seen in Figure 4.7. Regarding normalized surface beading, a product can theoretically have a maximum value of 2 x (3 exposed specimens) x (7 rounds of testing) = 42, which none of the products were able to achieve. The normalized surface beading of the "good" products spanned a range of 0 to 19 with an average value of 6, which is 2.5 times less than the average value of the "bad" products. While the surface beading test is a good initial test, the result indicates that it is not a reliable test to determine the water repellency of a treated surface.

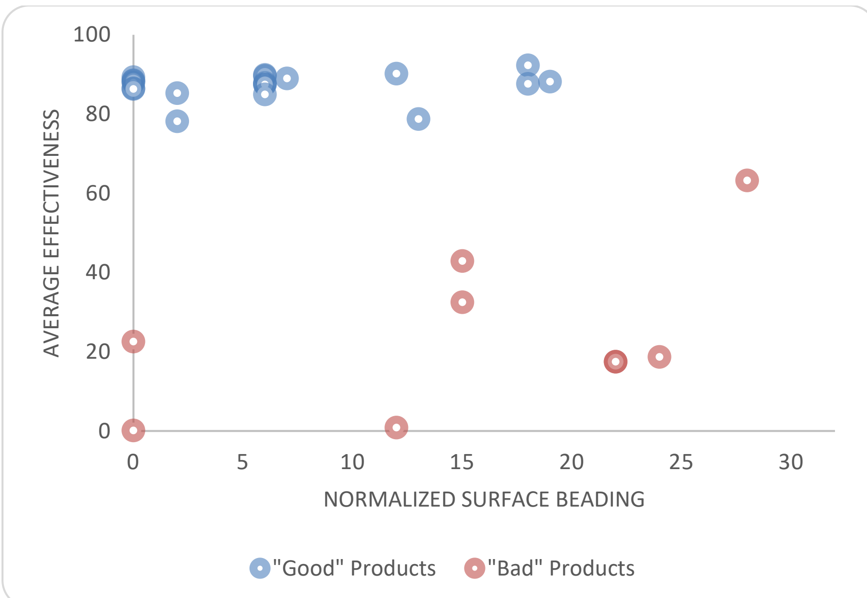


Figure 4.7: Normalized surface beading of the "good" vs. "bad" products after 37 months

While the effectiveness of many products remained excellent, Figure 4.8 shows that the cumulative surface beading exponentially decays over time, especially in the first 20 months following application. Beading ability is evidently not a accurate measurement to indicate treatment effectiveness, as surface beading is a superficial effect and is not related to the ability of a water repellent to prevent water infiltration and its long-term performance.

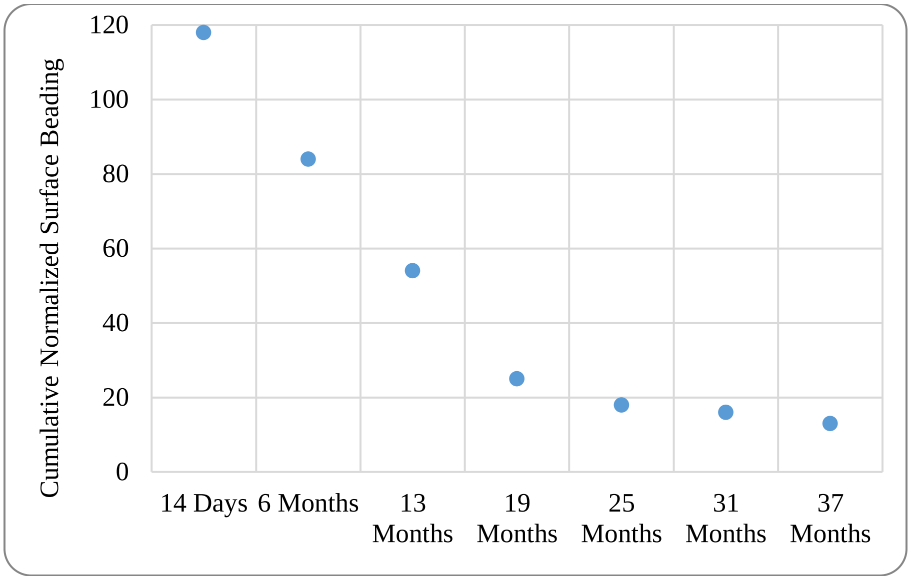


Figure 4.8: The cumulative normalized surface beading of 32 products over time

4.5 Results Summary of Water Repellents Testing

In this study, 32 products with different chemical composition and carriers were applied to terra cotta saucers and assessed using the most common tests in practice, which are recommended by the SWR Institute. Various characteristics were monitored over time to determine the effectiveness and durability of water-repellent treatments. The test results illustrate the necessity of including outdoor exposure in test standards to reflect the field performance of water-repellent treatments. Manufacturers should also publish the curing time so that specifiers are able to determine the suitability of a product for a given project. While beading ability is a good initial test, owners and contractors should understand that it does not dictate the efficacy of treatment.

The depth of penetration of a water repellent is also believed to improve the treatment durability; however, its relationship to the treatment effectiveness is still in question. A second round of testing conducted on another 32 products, which was started in April 2019, will include this parameter in evaluating the long-term performance of water-repellent treatments.

Chapter 5: Conclusion

Of all the issues to consider when building a structure, the durability of the building envelope involves perhaps the most complex set of physical interactions and the greatest potential economic consequences. It is necessary to include outdoor exposure when testing building envelope materials so that the test results are consistent with real-world application.

This research has been able to shed light on areas of confusion and to identify the factors that should be carefully considered by designers, builders, material manufacturers, and authorities. Many topics were established and relevant testing was carried out by focusing on practical issues that are known to create significant and reoccurring durability problems in building envelope materials. While this thesis specifically evaluates the long-term performance of flashings, plaster mixtures, and clear penetrating water repellents, the concepts and principles herein can be applied to a variety of conditions and applications in design and construction.

The testing of tapes and flashings shows that durability requires the appropriate use and installation of specified materials, substrates, and temperature. Modified asphalt has previously been the most popular adhesive to use in self-adhered flashing applications due to its relatively low cost. However, the shear adhesion study found that acrylic and butyl adhesives are not only more durable on many common construction substrates, but also behave consistently at a wide variety of temperature ranges. In addition to adhesives, top sheet materials also influence the durability of tape and flashing products. Indeed, the long-term exposure test indicates that a film top sheet is prone to degradation, while aluminum foil is more stable. This testing also proves the necessity of proper storage for flashing products. Moreover, research on adhesion requirements for tape and flashing products has demonstrated the inadequacies in the current governing codes and standards. The 16 psi of tensile adhesion required by ABBA can be achieved with ease by increasing the loading rate of the test – a parameter that is not well constrained by the D4541 standard. Despite the extensive framework of building codes and standards, gaps remain in terms of details and the reliability of information which need to be addressed in order to promote more durable practices.

The mechanical properties and CTE of various ASTM and pre-blended plaster mixtures were also determined in this research. It was found that the CTE is not only a function of the mixture proportion but also depends considerably on the moisture conditions. The CTE of fully saturated plaster may even be double that of dry plaster. This factor must be taken into account when specifying control joints for stucco cladding. Additionally, the study explored models that can predict the tensile strength and modulus of elasticity of a given plaster product from its compressive strength, which is an important parameter that manufacturers often choose to ignore. Testing would not be necessary if manufacturers could provide this information.

Finally, the results of water repellent testing indicate the need for long-term outdoor exposure, as the standardized durability test is not calibrated to performance in actual conditions. This behavior is demonstrated in the water absorption test, whereby a significant deficit was observed in the effectiveness of indoor vs. outdoor specimens for many products. This testing would help to inform installers about the best products to use. The SWR Institute is an excellent starting point to study the abovementioned test methods and requirements, as SWR Institute-validated products have been found to have very good quality during many tests at the Durability Lab. For developers, long-term outdoor exposure is necessary to indicate product performance even for a product that is already released onto the market. The study also shed light on the relationship between the beading ability and effectiveness of water repellents. An excellent product may not bead water, whereas a poor product may provide an exceptional beading effect. This beading effect is typically lost over time. Owners and specifiers should only use beading ability as a means to spot-check the applicator's work and not to measure the treatment effectiveness.

Premature failures could be avoided or at least subdued if manufacturers were to provide the product literature and guidance in detail. Manufacturers should also strive to develop their products with a high standard of performance instead of simply passing tests to make profits. Equally so, standards and codes need to reflect real-life applications and should be constantly updated so that specifiers and manufactures have the tools to promote durability. Durability is an investment. If builders and owners could pay a fraction more for consulting services and better products, then building durability failures would be far less common and costly maintenance and repair would be mitigated. As a professor used to say, "There is no high-performance concrete between cracks"; building durability is attributed not only to individual component durability, but the durability of all components that work together as a whole. As such, addressing this concept requires diligence from all parties.

Appendices

1. Tapes and Self-Adhered Flashings Testing

Year	Month	T Min	T Max	T Mean	Std. Dev	Temperature Normalization
2016	Jan	31	62	49	9	C
	Feb	33	82	60	10	A
	Mar	38	91	66	9	A
	Apr	45	90	69	8	A
	May	52	92	73	8	A-H
	Jun	65	98	81	7	H
	Jul	74	102	85	7	H
	Aug	71	103	81	7	H
	Sep	70	99	82	6	H
	Oct	49	89	72	8	H-A
	Nov	35	91	65	9	A
	Dec	22	85	52	12	C
2017	Jan	18	84	56	13	C
	Feb	38	89	63	11	A
	Mar	42	87	67	9	A
	Apr	49	94	71	8	A
	May	53	96	75	8	A-H
	Jun	66	101	80	7	H
	Jul	71	105	85	7	H
	Aug	69	101	82	8	H
	Sep	62	96	78	7	H
	Oct	39	92	73	11	H-A
	Nov	38	88	67	10	A
	Dec	29	84	49	11	C
2018	Jan	15	71	50	13	C
	Feb	29	82	54	12	C
	Mar	43	89	66	9	A
	Apr	39	88	66	10	A
	May	60	99	78	8	A-H
	Jun	68	101	84	7	H
	Jul	70	109	85	8	H
	Aug	72	103	85	8	H
	Sep	61	99	77	6	H-A
	Oct	42	91	69	11	A
	Nov	30	88	55	11	A-C
	Dec	35	82	52	9	C

Adhesive	Average Temp (55F-75F)		Cold Temp (40F - 55F)		Hot Temp (75F - 95F)	
	# of Specimen s	Avg Time to Failure, Day	# of Specimen s	Avg Time to Failure, Day	# of Specimen s	Avg Time to Failure, Day
Acrylic	42	19.4	18	20.5	171	17.2
Butyl	33	12.4	12	17.6	99	9.4
Modified Asphalt	27	8.7	15	18.3	102	7.2

2. Exterior Plasters Testing

PB1	Force, Lbs		
Gauge displacement, 10^{-6} in	Sample 1	Sample 2	Sample 3
60	2067	2333	1890
120	3722	3983	3604
180	5422	5701	5435
240	7000	7401	7035
300	8650	9039	8625
360	10132	10839	10125
420	11882	12589	11775
480	13234	13943	13588
540	15034	15004	15060
600	16158		

Mixture ID	Load at guage reading 0.00055 [lbs]	Stress at gauge reading 0.00055 [psi]	Load at ~ 0.4 f'c [lbs]	Stress at ~ 0.4 f'c [psi]	Gauge reading at ~ 0.4f'c	Strain corresponding to 0.4f'c	Modulus of Elasticity [psi]
PB2	2186	174	11600	923	0.0039	0.000368	2.37E+06
	1920.1	153	18000	1432	0.00628	0.000592	2.37E+06
PB3	2481	197	19600	1559	0.00558	0.000526	2.87E+06
	2215	176	19600	1559	0.006	0.000566	2.69E+06
	2126.9	169	19600	1559	0.006	0.000566	2.70E+06
PB4	2540.5	202	16100	1281	0.0052	0.000491	2.46E+06
	2983.6	237	18000	1432	0.00555	0.000524	2.53E+06
	3367.6	268	16000	1273	0.0056	0.000528	2.11E+06
PB5	2510.9	200	12100	963	0.0042	0.000396	2.19E+06
	1890.6	150	12000	955	0.0045	0.000425	2.13E+06
	2008.7	160	12000	955	0.00485	0.000458	1.94E+06

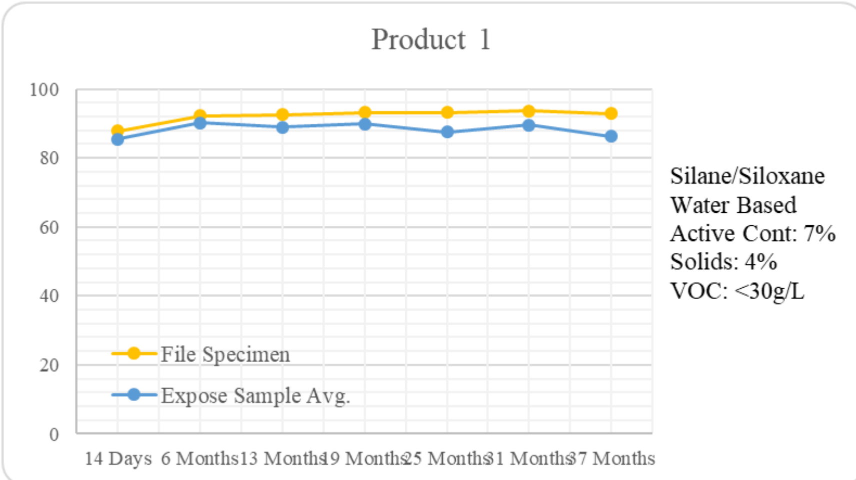
Dry Study						
Specimen ID		Specimen Length, in				
		70F	100F	125F	140F	70F
C926 Type C	A	9.9986	9.9996	10.0004	10.0009	9.9983
	B	9.9288	9.9298	9.9307	9.9312	9.9286
	C	9.9573	9.9583	9.9592	9.9597	9.9572
C926 Type CL	A	9.999	10	10.0008	10.0015	9.9984
	B	9.9582	9.9592	9.9598	9.9603	9.9575
	C	9.9441	9.9452	9.946	9.9466	9.9435
C926 Type M	A	9.9693	9.9707	9.9716	9.9721	9.9688
C926 Type CM	A	9.9267	9.9281	9.9289	9.9296	9.9261
	B	9.9704	9.9717	9.9728	9.9733	9.9698
	C	9.9693	9.971	9.9718	9.9724	9.9688
C926 Type MS	A	9.9844	9.9855	9.9863	9.9868	9.9838
	B	9.9844	9.9858	9.9866	9.9872	9.984
	C	9.9773	9.9785	9.9794	9.98	9.977

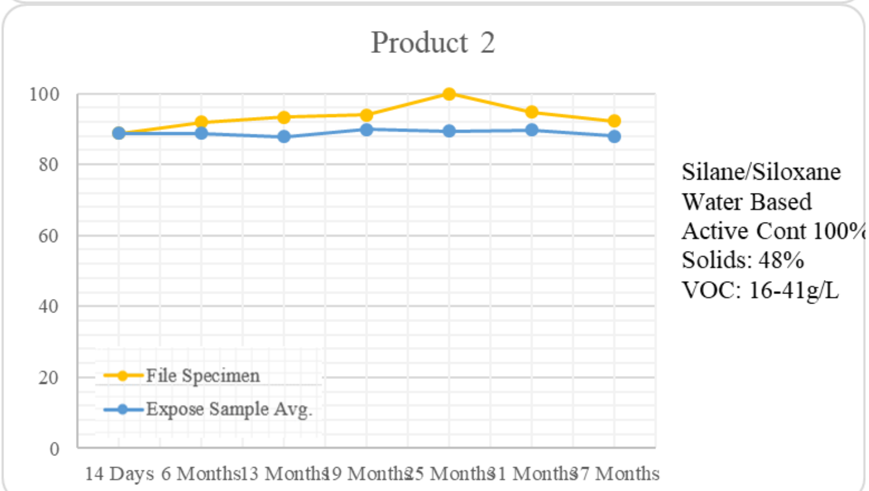
Dry Study					
Specimen ID		Specimen Length, in			
		100F	125F	140F	70F
PB2	A	9.9657	9.9666	9.9673	9.9640
	B	9.9903	9.9913	9.9922	9.9884
	C	10.0215	10.0227	10.0235	10.0200
PB3	A	9.9971	9.9981	9.9992	9.9948
	B	9.9711	9.9721	9.9731	9.9691
	C	10.0221	10.0234	10.0244	10.0203
PB4	A	10.0255	10.0265	10.0271	10.0236
	B	10.0575	10.0585	10.0593	10.0557
	C	10.0500	10.0509	10.0517	10.0478

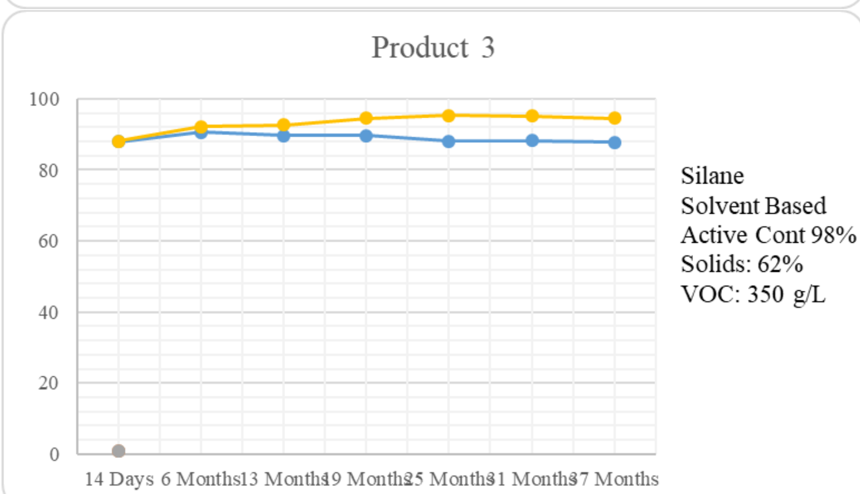
Wet Study						
Specimen ID		Specimen Length, in				
		70F	100F	125F	140F	70F
C926 Type C	A	9.9992	10.0014	10.0029	10.0041	9.9995
	B	9.9292	9.9315	9.9334	9.9346	9.9296
	C	9.958	9.9599	9.9618	9.9631	9.9584
C926 Type CL	A	9.9995	10.0016	10.003	10.0043	9.9993
	B	9.9587	9.9608	9.9622	9.9639	9.9587
	C	9.9447	9.9465	9.9484	9.9497	9.9445
C926 Type M	A	9.9702	9.9721	9.9738	9.975	9.9702
C926 Type CM	A	9.9276	9.9294	9.9311	9.9324	9.9275
	B	9.9716	9.9737	9.975	9.9763	9.9713
	C	9.9703	9.9721	9.974	9.9753	9.9705
C926 Type MS	A	9.9851	9.9868	9.9884	9.99	9.9849
	B	9.9849	9.9871	9.9886	9.9899	9.9849
	C	9.9781	9.9801	9.9815	9.9832	9.978

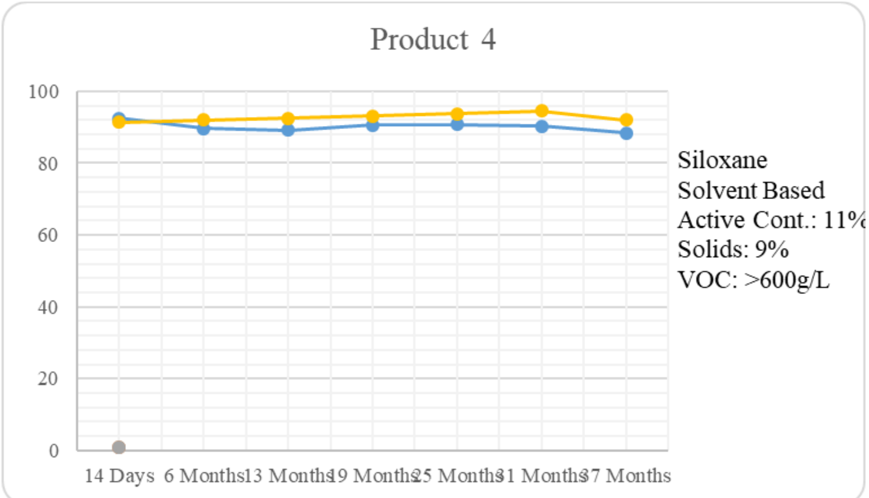
Wet Study						
Specimen ID		Specimen Length, in				
		70F	100F	125F	140F	70F
PB2	A	9.9992	10.0014	10.0029	10.0041	9.9995
	B	9.9292	9.9315	9.9334	9.9346	9.9296
	C	9.958	9.9599	9.9618	9.9631	9.9584
PB3	A	9.9995	10.0016	10.0031	10.0043	9.9993
	B	9.9587	9.9608	9.9624	9.9639	9.9587
	C	9.9447	9.9467	9.9484	9.9497	9.9445
PB4	A	9.9276	9.9294	9.9311	9.9326	9.9275
	B	9.9716	9.9737	9.9750	9.9765	9.9713
	C	9.9703	9.9722	9.9739	9.9751	9.9705

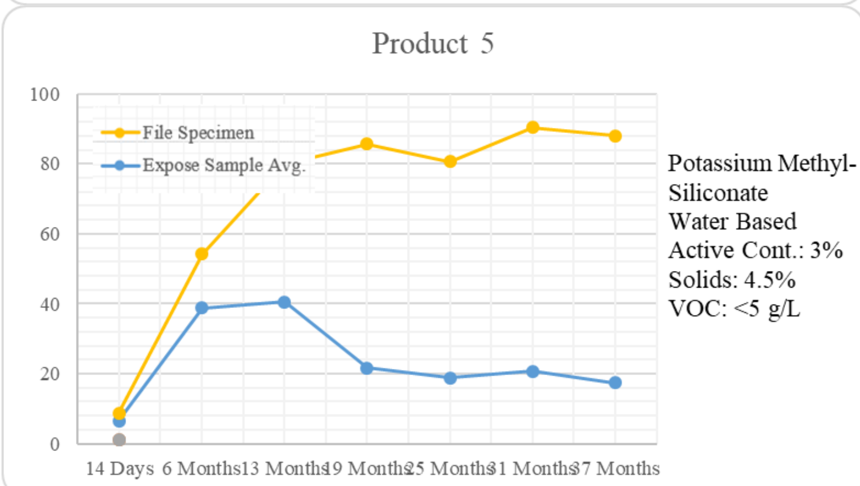
3. Clear Penetration Water Repellents Testing (Effectiveness)

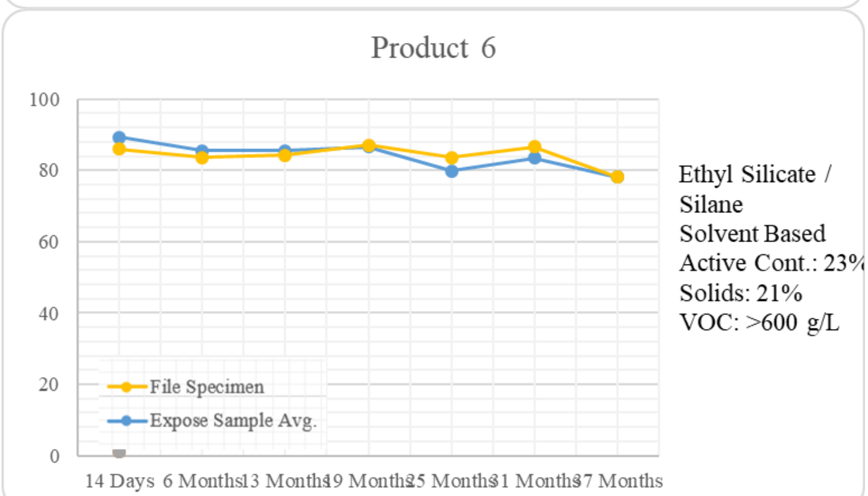


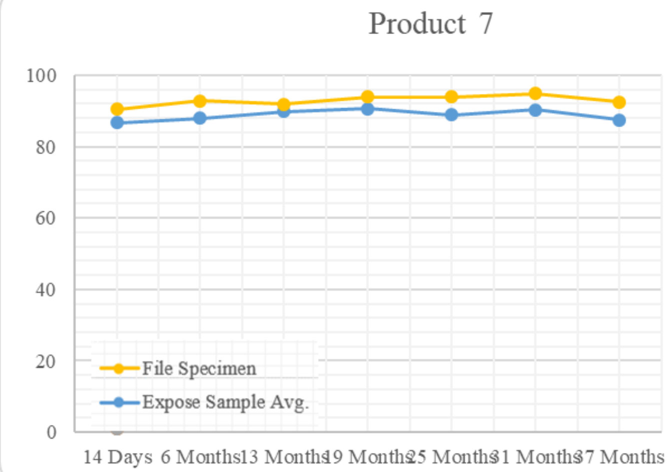




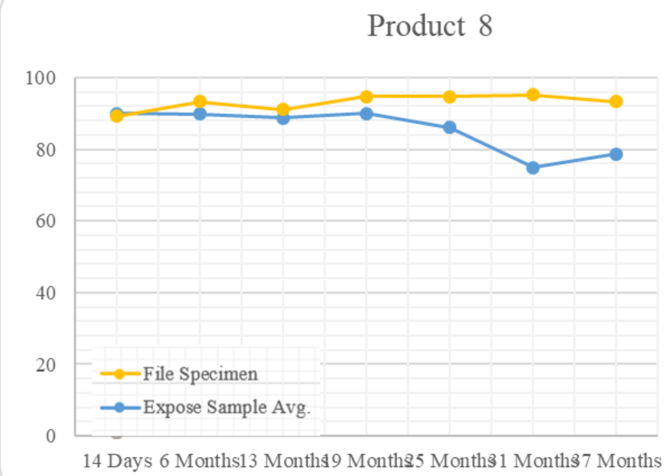

Product 4
100
80
60
40
20
0
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Siloxane
Solvent Based
Active Cont.: 11%
Solids: 9%
VOC: >600g/L


Product 5
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Potassium Methyl-
Siliconate
Water Based
Active Cont.: 3%
Solids: 4.5%
VOC: <5 g/L

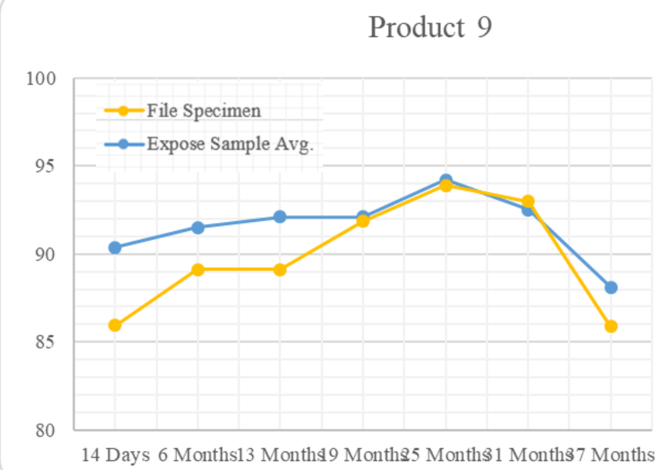

Product 6
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Ethyl Silicate /
Silane
Solvent Based
Active Cont.: 23%
Solids: 21%
VOC: >600 g/L



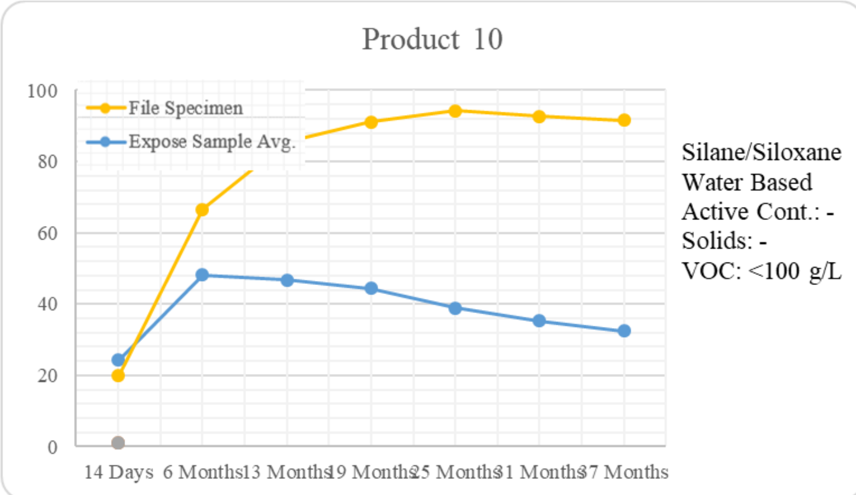
RTV-Silicone-Blend
Solvent Based
Active Cont.: 9%
Solids: 9%
VOC: >600 g/L

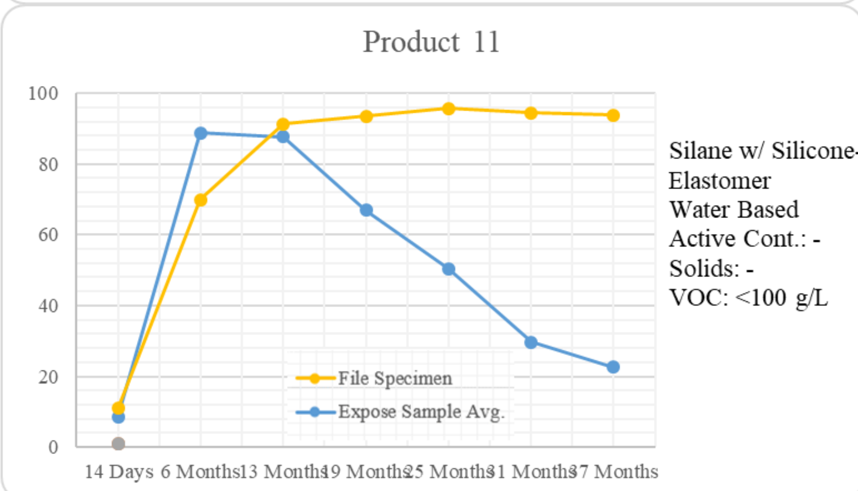


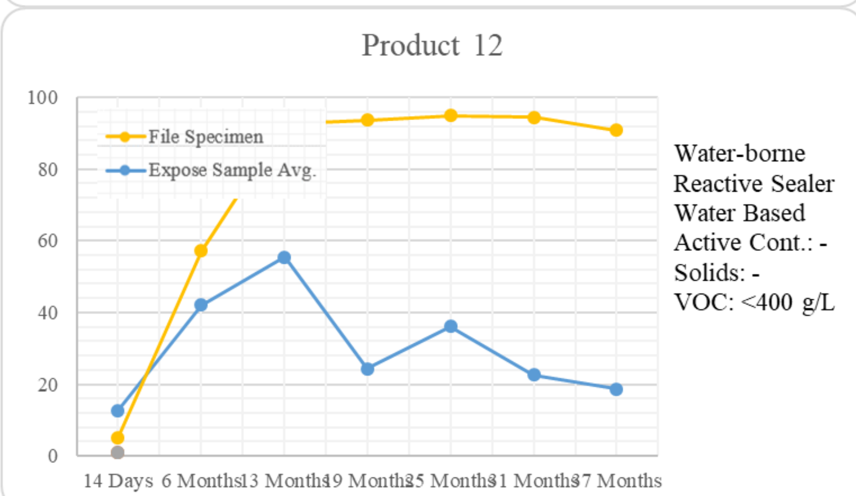
Silicone Emulsion
Water Based
Active Cont.: 6%
Solids: 6%
VOC: <20 g/L

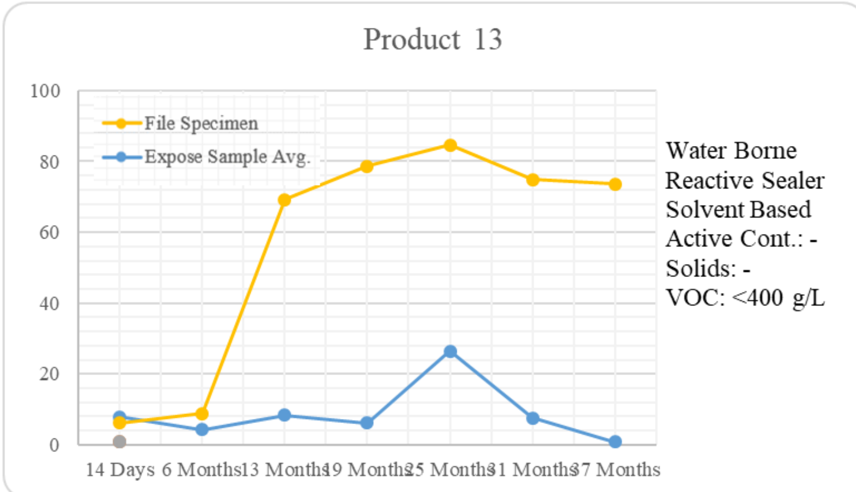


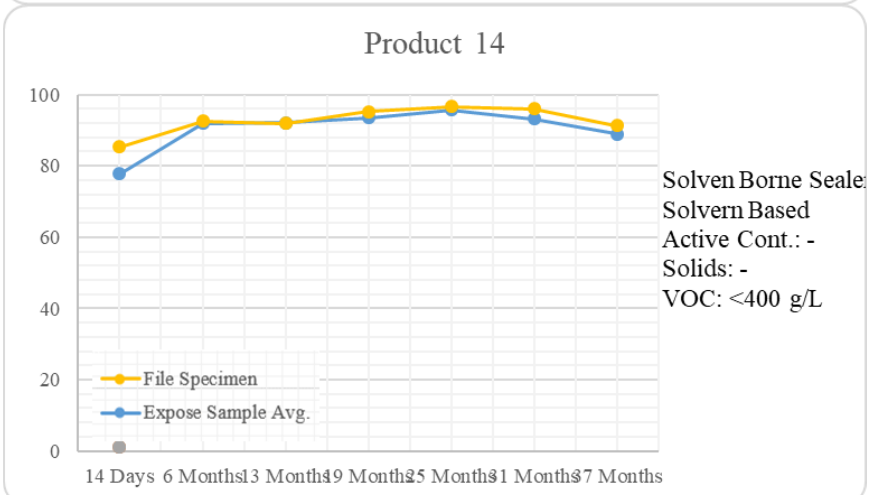
RTV-Silicone Blend
Solvent Based
Active Cont.: 9%
Solids: 9%
VOC: 100 g/L

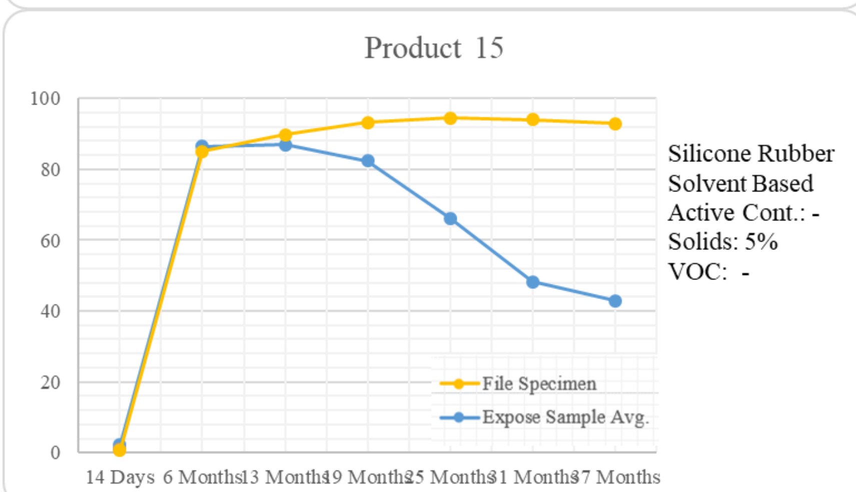

Product 10
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Silane/Siloxane
Water Based
Active Cont.: -
Solids: -
VOC: <100 g/L

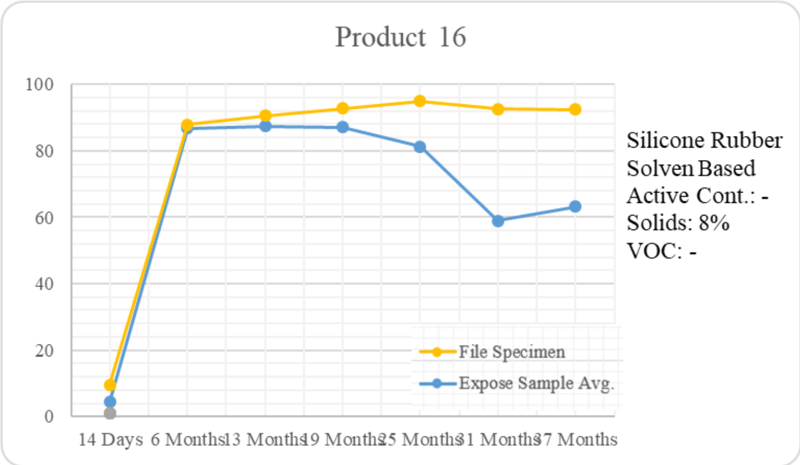

Product 11
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Silane w/ Silicone-
Elastomer
Water Based
Active Cont.: -
Solids: -
VOC: <100 g/L

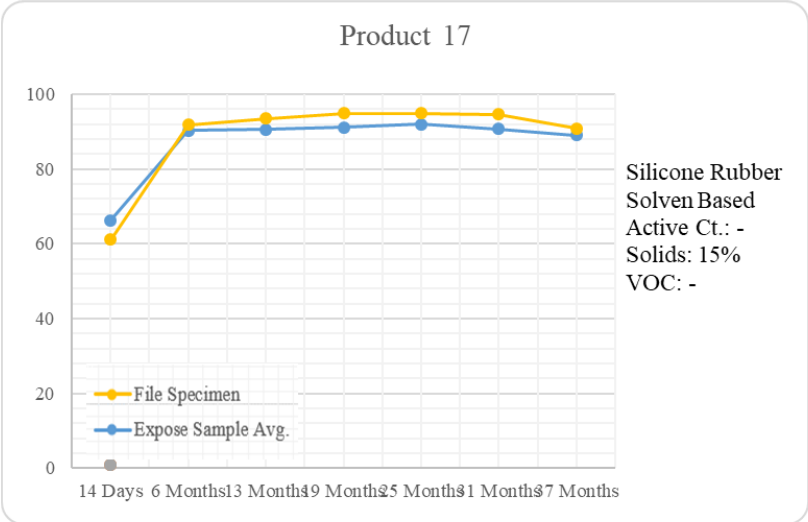

Product 12
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Water-borne
Reactive Sealer
Water Based
Active Cont.: -
Solids: -
VOC: <400 g/L

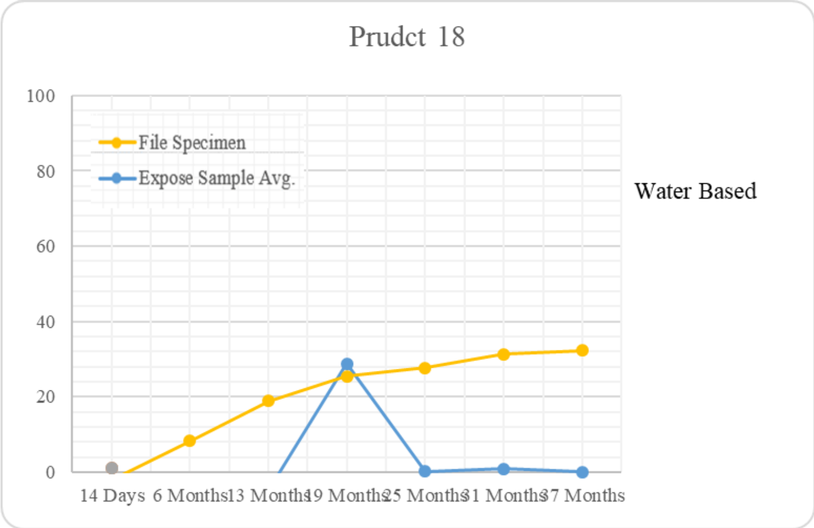

Product 13
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Water Borne
Reactive Sealer
Solvent Based
Active Cont.: -
Solids: -
VOC: <400 g/L

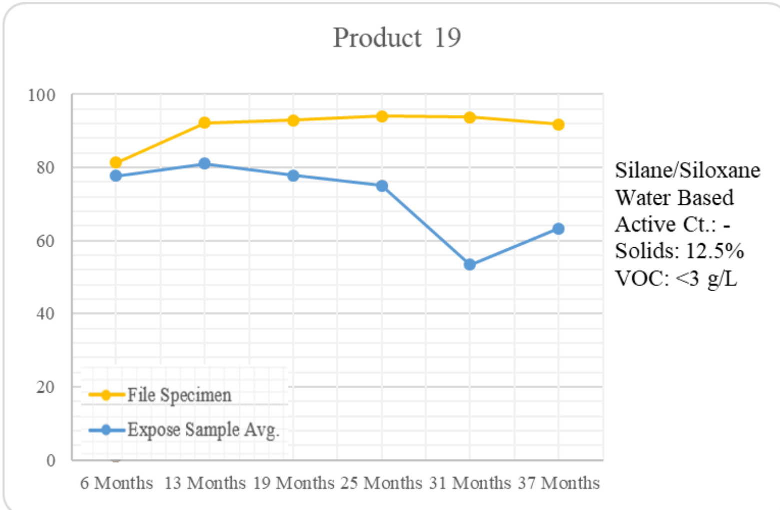

Product 14
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Solven Borne Seale
Solvern Based
Active Cont.: -
Solids: -
VOC: <400 g/L

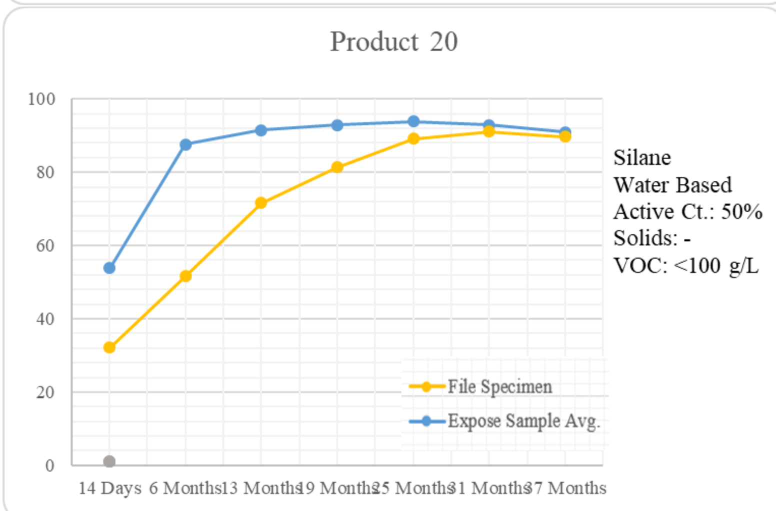

Product 15
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Silicone Rubber
Solvent Based
Active Cont.: -
Solids: 5%
VOC: -

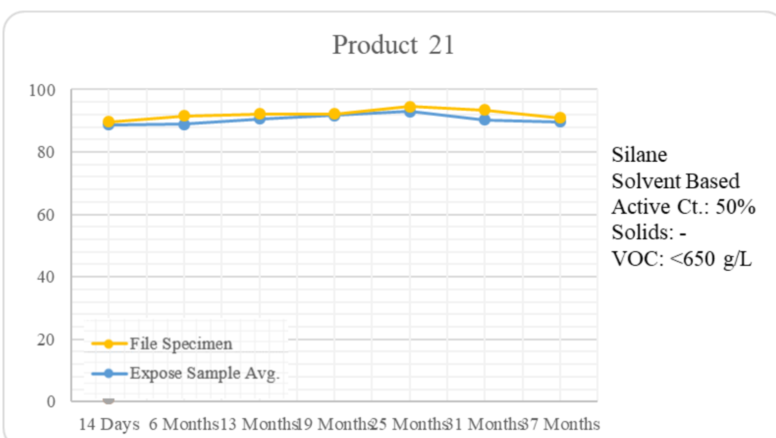

Product 16
100
80
60
40
20
0
14 Days 6 Months13 Months19 Months25 Months31 Months37 Months
File Specimen
Expose Sample Avg.
Silicone Rubber
Solven Based
Active Cont.: -
Solids: 8%
VOC: -

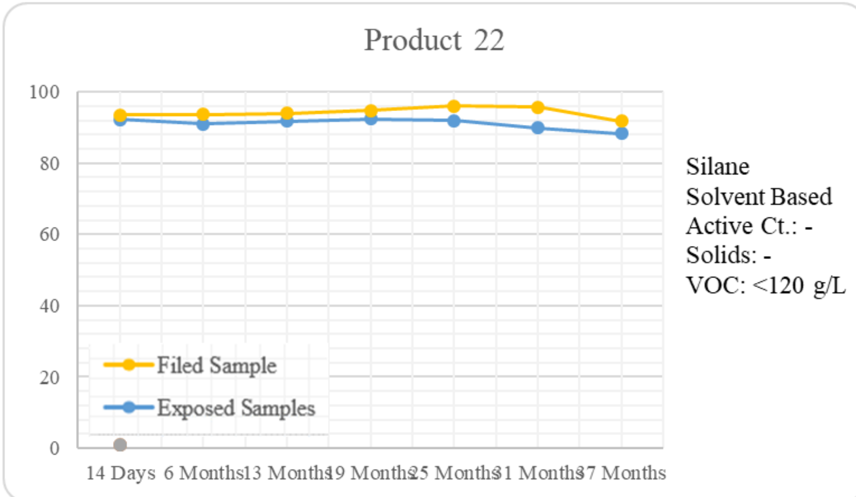

Product 17
100
80
60
40
20
0
14 Days 6 Months13 Months19 Months25 Months31 Months37 Months
File Specimen
Expose Sample Avg.
Silicone Rubber
Solven Based
Active Ct.: -
Solids: 15%
VOC: -

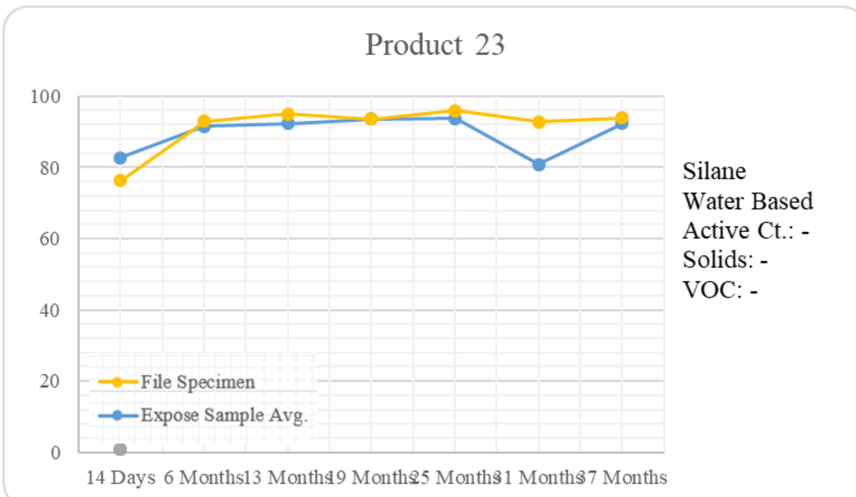

Prudct 18
100
80
60
40
20
0
14 Days 6 Months13 Months19 Months25 Months31 Months37 Months
File Specimen
Expose Sample Avg.
Water Based

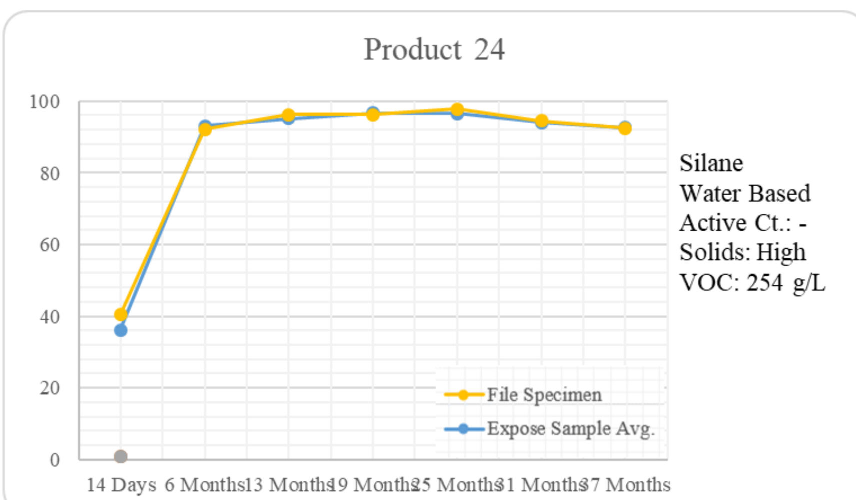

Product 19
100
80
60
40
20
0
6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
File Specimen
Expose Sample Avg.
Silane/Siloxane
Water Based
Active Ct.: -
Solids: 12.5%
VOC: <3 g/L

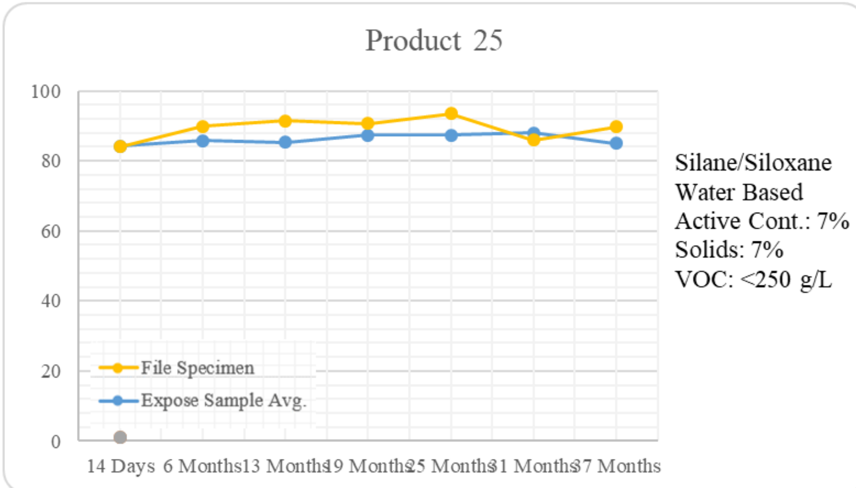

Product 20
100
80
60
40
20
0
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
File Specimen
Expose Sample Avg.
Silane
Water Based
Active Ct.: 50%
Solids: -
VOC: <100 g/L

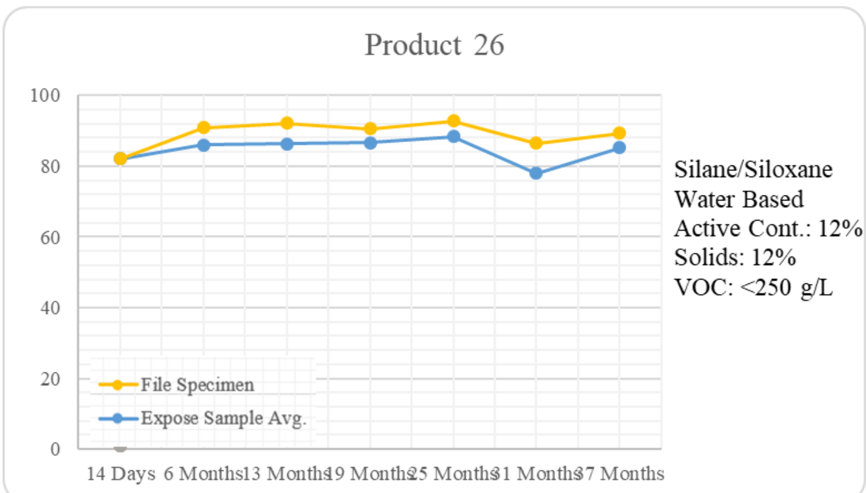

Product 21
100
80
60
40
20
0
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
File Specimen
Expose Sample Avg.
Silane
Solvent Based
Active Ct.: 50%
Solids: -
VOC: <650 g/L

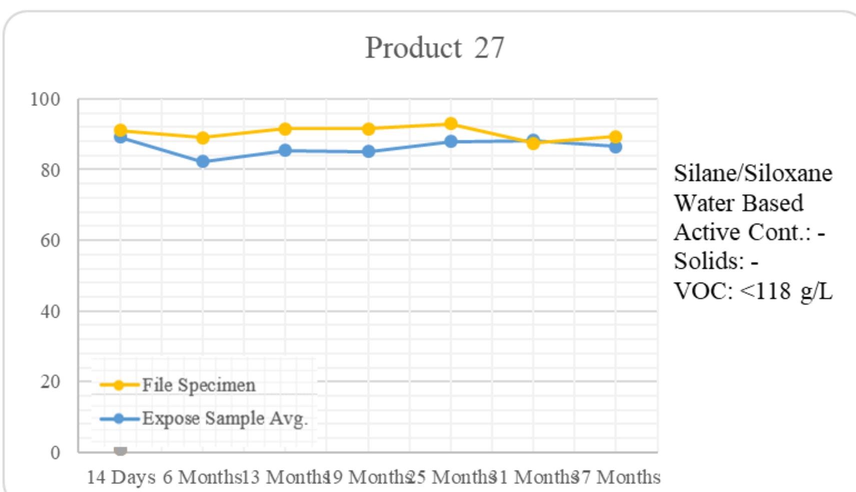

Product 22
100
80
60
40
20
0
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
Filed Sample
Exposed Samples
Silane
Solvent Based
Active Ct.: -
Solids: -
VOC: <120 g/L

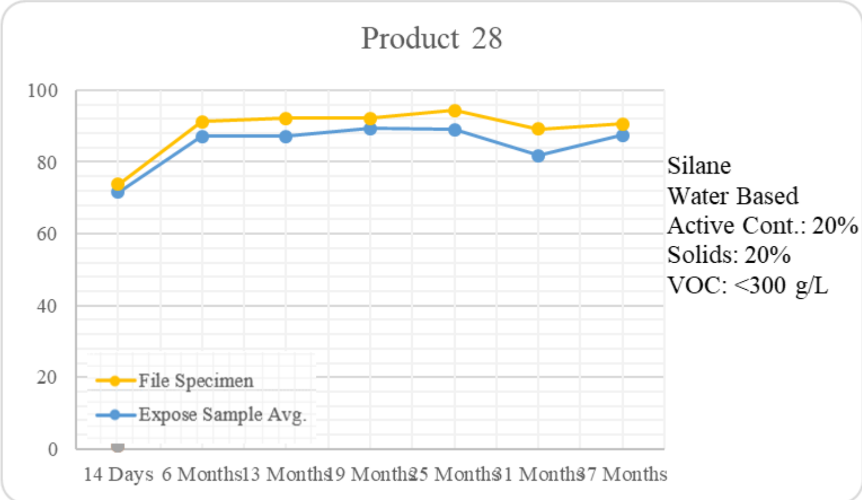

Product 23
100
80
60
40
20
0
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
File Specimen
Expose Sample Avg.
Silane
Water Based
Active Ct.: -
Solids: -
VOC: -

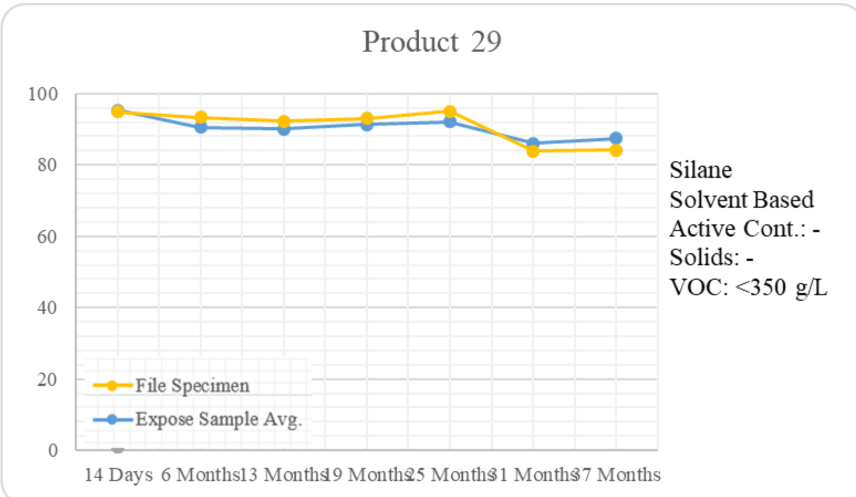

Product 24
100
80
60
40
20
0
14 Days
6 Months
13 Months
19 Months
25 Months
31 Months
37 Months
File Specimen
Expose Sample Avg.
Silane
Water Based
Active Ct.: -
Solids: High
VOC: 254 g/L

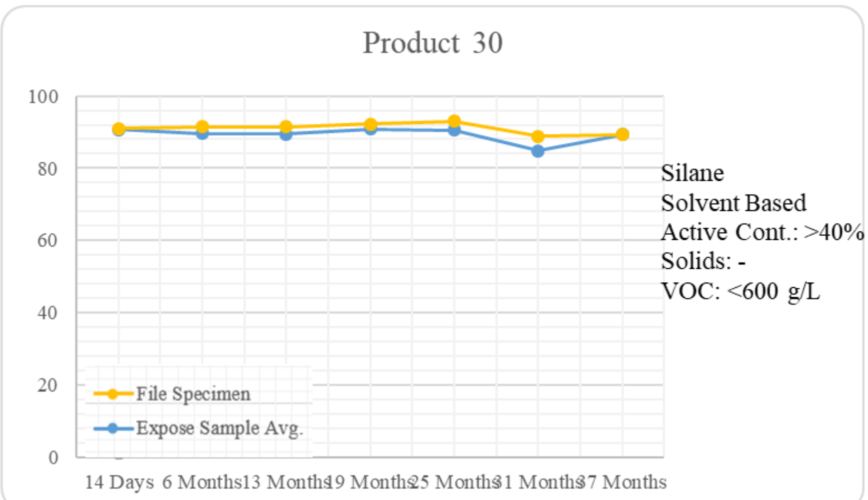

Product 25
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
Silane/Siloxane
Water Based
Active Cont.: 7%
Solids: 7%
VOC: <250 g/L

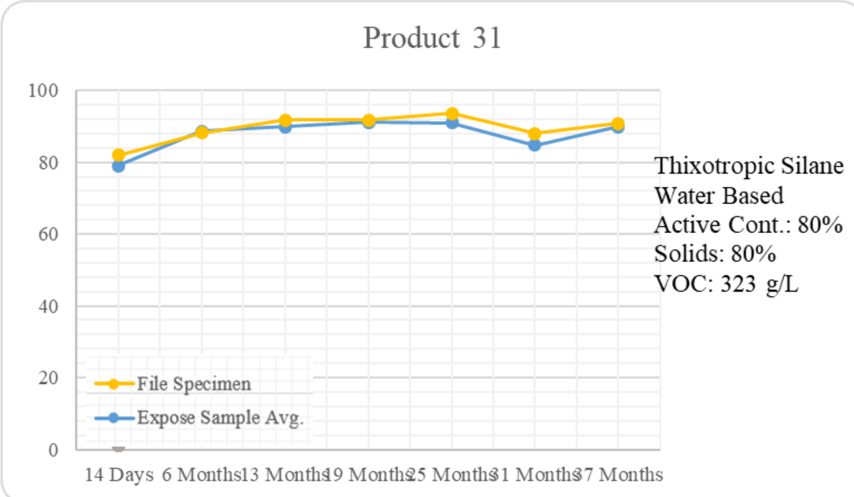

Product 26
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
Silane/Siloxane
Water Based
Active Cont.: 12%
Solids: 12%
VOC: <250 g/L

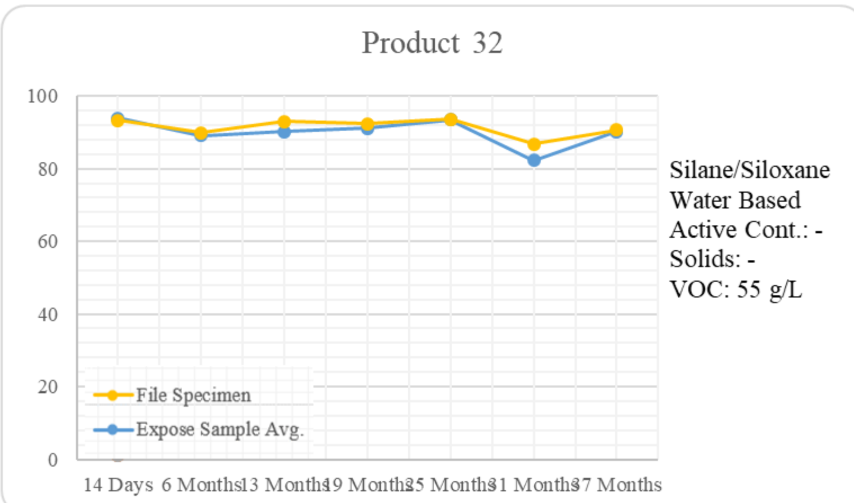

Product 27
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
Silane/Siloxane
Water Based
Active Cont.: -
Solids: -
VOC: <118 g/L


Product 28
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
Silane
Water Based
Active Cont.: 20%
Solids: 20%
VOC: <300 g/L


Product 29
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
Silane
Solvent Based
Active Cont.: -
Solids: -
VOC: <350 g/L


Product 30
100
80
60
40
20
0
File Specimen
Expose Sample Avg.
14 Days 6 Months 13 Months 19 Months 25 Months 31 Months 37 Months
Silane
Solvent Based
Active Cont.: >40%
Solids: -
VOC: <600 g/L





		Average Effectiveness						
Product Description		14 Days	6 Months	13 Months	19 Months	25 Months	31 Months	37 Months
"Good Products"	Expose	87	89	89	90	90	86	87
	File	87	91	92	93	94	91	90
"Bad Products"	Expose	14	52	54	49	44	31	29
	File	13	58	79	83	85	84	83

References

2012 *International Building Code*. Country Club Hills, Ill: ICC, 2011. Print.

2012 *International Residential Code*. Country Club Hills, Ill: ICC, 2011. Print.

2015 *International Building Code*. Country Club Hills, Ill: ICC, 2014. Print.

2015 *International Residential Code*. Country Club Hills, Ill: ICC, 2014. Print.

AAMA. *Voluntary Specification for Self-Adhering Flashing Used for Installation of Exterior Wall Fenestration Products, "AAMA 711-13"*, American Architectural Manufacturers Association (AAMA), Schaumburg, IL, July, 2013.

ABAA. *Process for Approval of Air Barrier Materials, Accessories, and Assemblies, "ABAA D-115-010 Rev 14",* Air Barrier Association of America Inc. (ABAA). 2015.

AC 148. *Acceptance Criteria for Flexible Flashing Materials*. ICC Evaluation Service. June 2006. Print.

ACI Committee 318. *Building Code Requirements for Structural Concrete: (ACI 318-14)*. Farmington Hills, MI. American Concrete Institute, 2014. Print.

Anthony M. Garcia, PE, and Jorge M. Blanco. "*Defining and testing construction tape and flashing durability*". The construction Specifier. December 14, 2017.

ASTM International. ASTM C67 / C67M-18, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*, ASTM International, West Conshohocken, PA, 2018. Print.

ASTM International. ASTM C97 / C97M-18, *Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone*, ASTM International, West Conshohocken, PA, 2018. Print.

ASTM International. ASTM C140 / C140M-18a, *Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units*, ASTM International, West Conshohocken, PA, 2018. Print.

ASTM International. ASTM C305-14, *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*. West Conshohocken, PA; ASTM International, 2014. Print.

ASTM International. ASTM C469/C469M-14, *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. West Conshohocken, PA; ASTM International, 2014. Print.

ASTM International. ASTM C496/C496M-17, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA; ASTM International, 2017. Print.

ASTM International. ASTM C596-18, *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement*. West Conshohocken, PA; ASTM International, 2016. Print.

ASTM International. ASTM C926-18b, *Standard Specification for Application of Portland Cement-Based Plaster*. West Conshohocken, PA; ASTM International, 2018. Print.

ASTM International. ASTM C1063-19a, *Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster*. West Conshohocken, PA; ASTM International, 2016. Print.

ASTM International. ASTM C1231/C1231M-15, Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Cylindrical Concrete Specimens. West Conshohocken, PA; ASTM International, 2015. Print.

ASTM International. ASTM D3330/D3330M-04(2018), *Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape*. West Conshohocken, PA; ASTM International, 2018. Print.

ASTM International. ASTM D3654/D3654M-06(2011), *Standard Test Methods for Shear Adhesion of Pressure-Sensitive Tapes*. West Conshohocken, PA; ASTM International, 2011. Print.

ASTM International. ASTM D4541-17, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*. West Conshohocken, PA; ASTM International, 2017. Print.

ASTM International. ASTM D6532-00(2014), *Standard Test Method for Evaluation of the Effect of Clear Water Repellent Treatments on Water Absorption of Hydraulic Cement Mortar Specimens*, ASTM International, West Conshohocken, PA, 2014. Print.

ASTM International. ASTM E2112-19, *Standard Practice for Installation of Exterior Windows, Doors and Skylights*. West Conshohocken, PA; ASTM International, 2019. Print.

C. Moreau, L. Leroux, V. Vergès-Belmin, G. Fronteau and V. Barbin. 2008, *Which Factors Influence Most the Durability of Water.* 5th International Conference on Water Repellent Treatment of Building Materials 129-142.

Chamra, Robert, and Beth Anne Feero. 2014. *Durable Waterproofing for Concrete Masonry Walls*. The Construction Specifier.

Gagnon, Kyle Richard. 2016. *Performance of Cladding and Waterproofing Materials.* Thesis, The University of Texas at Austin.

Katsaros, J., *Adhesive Characterization & Durability of Self-Adhered Flashings*. Journal of ASTM International, Vol. 2, No. 10, 2005, pp. 1-17.

NAHB Research Center, Inc., *Durability by Design, A Guide for Residential Builders and Designers.* May 2002. Print.

Saldanha, Adrian G., Eichburg, Doris E. *Testing the Test: Water Absorption with RILEM Tubes*. The Construction Specifier. August 2013. 18 August 2016. Web.

Technical Services Information Bureau. *Cracks in Portland Cement Plaster (Stucco).* Technical Bulletin. February 2008. Print.